Volume II

FALLOUT AND RADIOLOGICAL COUNTERMEASURES

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By *Carl F. Miller*

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Approved:

Robert A. Harker

ROBERT A. HARKER, DIRECTOR
MANAGEMENT SCIENCES DIVISION

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Chapter 7

NATURE AND PURPOSE OF RADIOLOGICAL COUNTERMEASURES

7.1 Explosion Phenomena and Countermeasures

A countermeasure system is defined here as any combination of actions, preparations, or use of protective facilities and equipments that reduces or eliminates the hazards, to humans and to physical resources, arising from the explosion phenomena of weapons of war. In the following discussion this definition is restricted to the types of weapons that would be used in a nuclear war; by implication, therefore, the definition includes actions that could be taken to maintain the life of survivors and to promote the recovery of societal functions in the period following the attack phase of the war.

Several explosion phenomena occur when a nuclear weapon is detonated, that interact with, and have an effect on, surrounding objects. Countermeasures designed to intercept and alter the interactions of these explosion phenomena with surrounding objects, so that the magnitude of the effect of the interactions is reduced or eliminated, may be termed receptive countermeasures. The consideration of the use of receptive countermeasures is based on the possibility that the phenomena may occur.

A simple but fundamental statement about receptive countermeasures is that both their nature and their composition must be deduced from information on both the phenomena and the target. The statement is fundamental because it requires that countermeasures be identified and specified directly from the identification of the explosion phenomena and from the specification of the effects of these phenomena on people and human resources.

The major phenomena of nuclear explosion are identified as: (1) initial nuclear radiation, (2) thermal radiation, (3) blast and shock, and (4) residual radiation or fallout. The first three occur within a short time after the explosion; their isointensity patterns on a surface are circular about the point of detonation. The residual radiation or fallout phenomenon (as a hazard) develops over a period of time after the explosion; the fallout radiation isointensity patterns have elongated shapes extending a considerable distance downwind from the point of detonation.

The magnitude of the radiation intensity from fallout would be largest when the explosion occurs near the surface of the earth; in fact, air detonation fallout

is usually neglected as an immediate personnel hazard. Secondary effects from the initial explosion phenomena, such as fires ignited by the thermal radiation, may last for some time afterward but they would not be a source of concern for as long a time as the radiological hazard from fallout.

This listing of the four major phenomena of nuclear explosions is not a new one; all are well recognized. Two major significant points about them should be emphasized: 1. The physical nature of each of the four phenomena is different from that of any of the others in one way or another; hence, technical considerations of protective countermeasures must account for each of the four separately. 2. The operational use of countermeasures must consider the intensity pattern of the combined phenomena, including the time-sequence of each, and the cumulative effect of their interactions with the environment.

The general technical natures of the receptive countermeasures applicable to each of the explosion phenomena are also fairly well known. The countermeasures include:

1. Shielding: to reduce the gamma ray intensity and neutron flux of the initial nuclear radiation;

2. Shielding, fire-prevention techniques, and employment of fire-control methods: to reduce the effects of exposure of people and property to both thermal radiation and fire hazards;

3. Shielding and heavy construction: to reduce damage from blast and shock; and

4. Shielding, decontamination, and exposure-control methods: to reduce the exposure of people and animals to the nuclear radiation from fallout.

The countermeasure common to all four explosion phenomena is shielding.

Evacuation and distance are not included here as receptive countermeasures since they do not specifically operate against any one of the phenomena. Evacuation is a preventive rather than a protective measure; its successful use (for mobile objects) generally would require prior information about the location(s) of the explosion(s). Distance, aside from its identification with evacuation, is most often associated with the decrease in intensity of nuclear radiation from a single point source of radioactivity. However, in a fallout area where point sources are everywhere, distance is not an effective countermeasure except for the case in which the sources are removed, as in a decontamination process. In this sense, the term distance may be included as part of the decontamination countermeasure.

If a potential response level of humans (or other objects) to the intensity of the four phenomena is selected, such as the intensity that could result in a large fraction of fatalities, then statements can be made about the relative order in the size of the affected areas enclosed by each of the phenomena for the selected response level. For example, the relative sizes of the areas enclosed by the four phenomena from the detonation of a standard nuclear weapon in the megaton yield range near the surface of the earth, where the perimeter of the affected areas is defined by a (potential) response level equivalent to about 50 percent human fatalities, are, largest to smallest: (1) fallout, (2) thermal radiation, (3), blast, and (4) initial nuclear radiations. In this example, the area covered by radiation levels high enough to produce the stated minimum level of potential response would be nearly 100 times larger than the area affected by thermal radiation and giving the same effective response (i.e., about 50 percent deaths).

A single detonation of the same type of nuclear weapon at an optimum height in the air would give the order of area coverage, largest to smallest: (1) thermal radiation, (2) blast, and (3) initial nuclear radiations.

If objects other than humans were selected for consideration at a given potential response level, a different order of area coverage for the four explosion phenomena could result. For example, the radiation from fallout has no effect on most physical objects. Some objects are more susceptible to damage by blast and shock than they are to thermal radiation. For a single surface detonation in which all four phenomena occur it is clear that, of the total affected area, the largest fraction would be affected by fallout only. Smaller portions of that area would be affected by thermal radiation only, by fallout and thermal radiation, by thermal radiation and blast, by fallout, thermal radiation, and blast, and by all four phenomena simultaneously. If the affected area for the surface detonation is examined in terms of the response of inanimate objects, it can be reduced to about the area coverage of the three immediate phenomena.

In general, two characteristic areas may be identified. One is the portion of the affected area that receives fallout only and would contain undamaged structures and facilities. The other is the smaller portion of the whole affected area that receives thermal radiation and blast effects; this would contain physically damaged facilities and people. The shape of this smaller area, while determined to a large extent by its physical nature, would be more or less circular around the point of detonation. The degree of damage within it, also dependent on its physical nature, would increase as the distance to the point of the explosion decreases.

Where the order of development of a countermeasure system follows the order of the sizes of the areas affected by the explosion phenomena, the stepwise procedure would be to:

1. Provide protection against fallout (i.e., radiological countermeasures).

2. Add protection against thermal radiation effects, where needed (i.e., fire prevention and control countermeasures).

3. Add further protection against blast and shock and initial nuclear radiations, (i.e., blast shelters).

Accomplishment of the first step would reduce the area affected by fallout, the area characterized by undamaged facilities, as well as reducing some portions of the areas affected by the other phenomena. In other words, a shelter that provides adequate shielding against the nuclear radiations from fallout also provides some level of protection against thermal radiation and blast or shock. Protection against thermal radiation and its effects could be added, in the second step, in locations where the fire potential of an area is considered to be high. Blast protection could be provided, in the third step, where the population density is high or where the location is considered--perhaps on strategic grounds--to be a prime target in a nuclear war.

For the case of a single nuclear explosion near the earth's surface, two characteristic areas may be identified. In the one affected only by fallout, no physical damage occurs directly from the other phenomena of the explosion; in the other, physical damage does occur. In a nuclear war, in which several or many nuclear explosions take place over the country, a third characteristic area can be identified: the "unaffected" area. The term does not mean that the people in the third area would not be affected by a nuclear war, or that the area would not receive some fallout. By definition, the unaffected area would be outside the affected area and, although the boundary between the two may be defined in a variety of ways, the general features of the unaffected area would be that it contains no physically damaged facilities and that it receives less than a stated level of fallout.

A possible definition of the perimeter of the area that is affected by fallout would be one given in terms of the radiation level at which the general movement of people would (or should) be restricted because of exposure to the nuclear radiations from fallout. Then, because of the decay of the radioactivity in fallout, the unaffected area would increase with time after the war and the area affected by fallout only would decrease. The applications of this definition of the perimeter, and detailed descriptions of the three areas, are given in Section 7.2.

Radiological countermeasures are particularly applicable to the areas affected by fallout only. Initially, these countermeasures have at least two important local functions as part of a larger countermeasure system or civil defense organization: first, to reduce the exposure of people to the nuclear radiations from fallout; second, to recover the use of the undamaged facilities in the area as soon as possible. These functions and the methodology for carrying them out are discussed in some detail in the following chapters.

7.2 The Affected Areas and Countermeasures

7.2.1 General Classification of Affected Areas

The discussions of the previous section, supported by and derived from war-gaming studies of nuclear attacks, show that the areas affected by the explosion phenomena of nuclear weapons (blast and shock, initial radiations, thermal radiations, and nuclear radiations from fallout) can be separated into three classes of areas, depending on the severity (or intensity) of each of the explosion phenomena and on the manner in which each phenomenon interacts with the environment.

Because of the spatial distribution of targets and wind patterns, some areas would receive only worldwide (low level) fallout in an attack. These areas would be otherwise unaffected, at least directly, by the four major weapon phenomena, and are termed FREE areas. Movement of people and nonhuman resources in these areas would be unrestricted, and no protective measures would be required to assure immediate short-term survival of their people and nonhuman resources.

Other areas of the country would receive sufficient local fallout deposits to require some level of protection, so as to keep radiation exposures below a stated level or to prevent fatal exposure levels; these are termed RADEP (i.e., radioactive deposit) areas. Outdoor movement of people in these areas would be restricted temporarily because of the nuclear radiation from fallout. In these areas the major protective and recovery countermeasure actions include stay in sheltered locations, for various periods of time, depending on the level of the fallout deposit, and decontamination of exposed surfaces (paved areas, roofs, land areas, etc.).

Areas nearest to the explosion points would receive physical damage from the blast and thermal radiation phenomena; these are termed DAMAGED areas. In addition, these areas would receive the fallout from both low air bursts and land-surface explosions, or at least from the detonations causing the damage. In these areas, the major protective countermeasure for people is shelter. The use of other possible countermeasures is discussed below.

Identification of the three basic area types, namely the FREE, RADEP, and DAMAGED areas, is most significant with regard to (1) sorting out the various countermeasure actions applicable to each, (2) arranging the priority of the alternate operations that are possible, and (3) specifying the options available to civil defense authorities in organizing recovery actions. But first it is important to focus attention on how the three types of areas may be identified and on how and when the boundaries between them may be located.

7.2.2 Approximate Methods For Locating The Initial Boundaries of The Three Major Areas

The boundary line(s) between any two of the three characteristic areas can be established best by illustrative example. This may be done by first considering the boundary between the FREE and RADEP areas for the fallout from a single land-surface detonation. In a sense, this boundary can be established or defined on an operational basis because in the FREE area operations would at no time be restricted because of radiological hazards and, in the RADEP area, at least the outside operations would be restricted for some time because of exposure of people to the gamma radiation from fallout. The definition of the boundary between the two areas on the basis of freedom to conduct outside operations results in a boundary that moves with time. The perimeter of the RADEP area moves inward as the radioactive nuclides in fallout decay; and the RADEP areas, in general, will disappear altogether, in about one to two years after attack, even if no radiological countermeasures are used. The RADEP areas would not be created by detonations at high altitudes.

Unshielded operations in radiation fields may be conducted at any location or area if the exposure(s) to nuclear radiation of the people carrying out the operation results in exposure dose(s) that are less than some stated amount. Since it would be desired that the continued capability of people to do useful work be maintained over a period of time, the initial allotments of dose in early operations must not exceed the threshold for radiation sickness. If such an allotment of exposure is prescribed for the early exposures, then many necessary operations can be conducted over a period of time without subsequent losses in the surviving work force due to possible radiation effects. Both biological recovery and radioactive decay would tend to limit the biological damage in later exposures.

Consideration of these factors leads to a suggested infinity dose of about 100 roentgens as the potential exposure dose for the initial definition of the boundary between the RADEP area and the FREE area. In other words, in fallout areas where the estimated infinity exposure dose--the outside-of-shelter exposure dose from time of fallout arrival to about 2 years later--is less than 100 roentgens, no one needs to stay in shelter, but could if no actions

were planned. If the exposure dose is more than this amount, the inhabitants should stay in sheltered locations for appropriately longer times.

The next question for consideration is how and when someone can determine whether a given location would be within the RADEP area or not. The answer to this question may be derived from examination of data on (1) fallout arrival times, (2) the variation of air ionization rates (i.e., dose-rates) with time, and (3) the decay of fallout radiations with time.

Data for a 5-MT yield land-surface detonation (50 percent fission) as well as some data for a 15-MT surface detonation (also 50 percent fission) were used to derive an approximate relationship between the time of fallout arrival and the maximum ionization rate which, in general, defines the location at which the infinity dose is 100 ± 20 roentgens. This is approximately given by

$$I(\max) = \frac{20}{t_a} \tag{7.1}$$

where I (max) is the maximum observed dose rate and t_a is the arrival time of the fallout in hours. Thus, if fallout starts arriving at 1 hour after detonation and the highest observed radiation intensity is 10 r/hr before the intensity starts to decrease, the location is in the FREE area. If the maximum observed intensity is greater than 20 r/hr, the location is in the RADEP area.

When the fallout from more than one detonation is involved, the smallest t_a value should be used along with I (max) if the various detonations which contribute to the radiation levels are close enough together in location and time to result in a more or less continuously rising intensity for several (4 to 6) hours. If the detonations producing the fallout were spaced over several days' time, account would have to be taken of the doses in previous exposures and the value of 20 should be decreased in proportion to the levels already received.

If the weapon (s) had less than 50 percent fission, I (max) would be decreased proportionately for a given value of t_a; in this case the rule of thumb would be a conservative guide. For a single detonation, the rule appears to hold within the stated reliability for times of arrival from about 20 minutes (i.e., within the DAMAGED area) to about 24 hours. For locations at which arrival times of more than 24 hours occur, the infinity dose will never exceed 100 roentgens (given any weapon yield in the range of 5 to 25 MT with a 50 percent fission yield).

The rule of thumb can be applied only if the observer has a watch to measure the time between the flash (or sound from the blast wave) and the time of fallout arrival, and a radiation detector to determine what the

maximum radiation rate is when the fallout arrives. For arrival times longer than several hours, the peak radiation rate should occur, for an average wind speed of about 20 mph, about 2 hours after the fallout arrives. No studies as yet have been made of the effect of wind speed on the rule of thumb.

The boundary between the DAMAGED area and either the RADEP or FREE areas is quite simple to define in terms of the observed effects on the area. In these terms the existence of physical damage such as broken glass from the blast wave or fires from the thermal radiation would suffice to specify that the location would be in the DAMAGED area. Of the latter of the two effects, the fires, would provide the more spectacular evidence of the DAMAGED area boundary and would tend to give the larger area for larger detonation yields. The identification and location of this perimeter would require no special instruments.

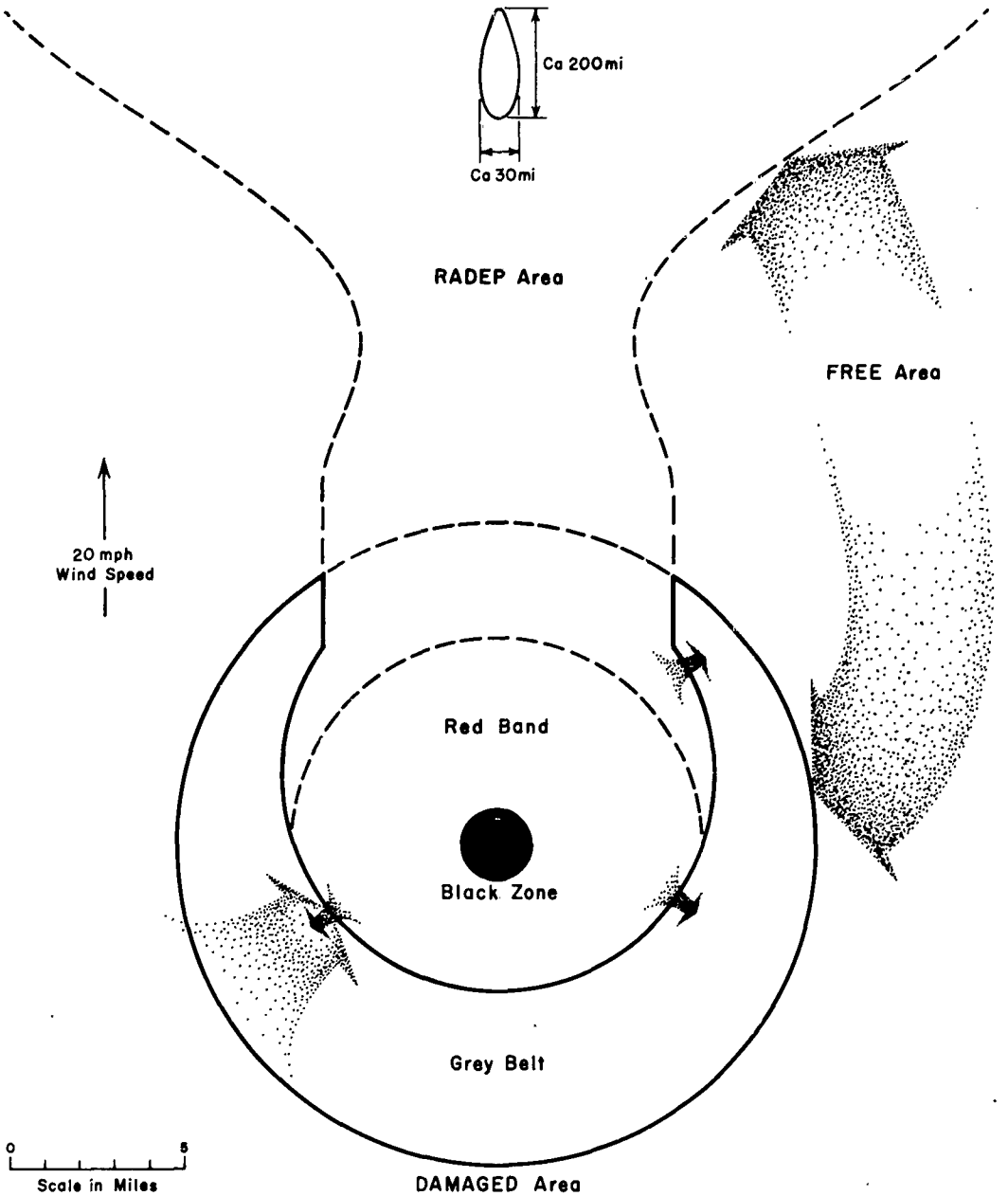
Inside the DAMAGED area, the damage and destruction of nonhuman resources and the number of injured and killed people would increase as the distance to the center of the area at ground zero decreases.

Two observable criteria have been presented for making an approximate determination at a location to which one of the three basic area classifications apply. The next step is to examine, in a little more detail, the affected areas themselves so that the influence on civil defense operations of the characteristic target responses to weapon phenomena can be brought into view.

7.2.3 The Grey Belt, Black Zone, and Red Band of the Damaged Area

As shown in Figure 7.1, just inside the DAMAGED area from a single detonation a Grey Belt exists in which transattack and/or postattack operations could be conducted without any restriction on the operations due to exposure of operating personnel to the nuclear radiations from fallout. The Grey Belt would contain physically damaged objects but little fallout from the detonation that caused the damage. Because the effects of the blast and shock phenomena would occur over a short period of time, and fires, which would be initiated immediately, would take some time to develop into large-scale conflagrations (even if the weather and fuel conditions in some cities were favorable for the development of large-scale fires), it is useful to examine the use of the 100 roentgen infinity dose criteria for applicability to defining, initially, the inner boundary of the Grey Belt within which outside operations could be conducted without restriction due to fallout.

Figure 7.1
APPROXIMATE DIMENSIONS OF COUNTER MEASURE ACTION AREAS FOR A 5-MT YIELD LAND-SURFACE DETONATION (50 percent fission)



This inner boundary could, in some instances, be defined by either the initial boundary of the DAMAGED area on account of the thermal effects, or by the periphery of a conflagration if large-scale fires developed in some parts of the area. Any one of these definitions of the Grey Belt within the DAMAGED area would have operational significance with respect to the conduct of civil defense countermeasure actions. To describe how the inner boundary of the Grey Belt could be identified and recognized according to the 100 roentgen infinity dose criterion, it is necessary to summarize selected data which describe, in some detail, what might be seen at locations in the DAMAGED area shortly after a nuclear detonation.

Local situations in the DAMAGED area upwind from the point of detonation of a 5-MT yield land-surface detonation are summarized as follows:

1. Upwind distance to the 100 roentgen infinity exposure dose contour . . . 4.2 miles.

2. Overpressure at 4.2 miles . . . 6 psi.

3. Damage picture (blast only) at 4.2 miles: frame houses flattened; brick houses and apartment buildings blown over; exterior walls of multistory wall-bearing monumental buildings and reinforced concrete buildings badly cracked, interior partitions badly cracked or blown down, structural frame distorted, extensive spalling of concrete; heavy steel-frame industrial buildings (25-50 ton crane) sustaining some distortion to the frame; larger, heavier buildings showing smaller amounts of damage; cars and trucks turned over, displaced, badly dented, frames sprung; trees uprooted; telephone poles broken; railroad car doors demolished, frames distorted; debris in streets in built-up areas.

4. Distance to 2 psi overpressure . . . 8 miles.

5. Distance to thermal ignitions in houses (colored curtains, upholstery, etc.) . . . 9 miles.

The situations in the crosswind direction from ground zero for this detonation are as follows:

1. Crosswind distance to the 100 roentgen infinity exposure dose contour . . . 5.8 miles.

2. Overpressure at 5.8 miles . . . 4 psi.

3. Damage picture (blast only) at 5.8 miles: about the same as for the 6 psi distance, except some frame houses will not be completely collapsed, and some brick house and apartment-type buildings may have exterior walls only badly cracked; lesser damage to the larger buildings.

4. Time of fallout arrival . . . 20 minutes.

Based on the 100 roentgen dose criterion, whether a location would be within the boundary of the Grey Belt (in the upwind and crosswind directions, if known) could be determined roughly from early observed blast and thermal effects. For example, locations at which frame houses were not completely destroyed, trees were not uprooted, outside cars were not turned over or displaced and the debris on the streets permitted easy travel would be within the Grey Belt.

At the inner boundary of the Grey Belt, essentially all the people in the open at the time of detonation, unless shadowed by some object, would be fatally burned by the initial thermal flash. If the atmospheric visibility was 10 miles, the thermal radiation on the inner perimeter of the Grey Belt, defined by the 100 roentgen criterion, would be between 50 and 100 calories per sq.cm. In this range of incident thermal radiation, essentially all combustible materials will ignite, at least to the point of sustaining a flash-flame.

The general effects on people at the inner perimeter of the Grey Belt may be approximately given from comparisons with the data on the survival rates of the Japanese people of Hiroshima and Nagasaki during World War II. These are as follows:

1. Survival rate, 50 to 100 cal/cm^2, direct outside exposure 0.0

2. Survival rate, 50 to 100 cal/cm^2, in buildings* . . 0.9 to 1.0

3. Survival rate, 4 to 6 psi, outside . . . . . (see No. 1)

4. Survival rate, 4 to 6 psi, in frame buildings*. . . 0.85 to 0.9

5. Survival rate, 4 to 6 psi, in concrete buildings*. 0.95 to 1.0

6. Survival rate, 4 to 6 psi, underground shelters . 1.0

*May be gutted by fires over a period of time.

These survival rates include both injured and uninjured people. The over-all survival rates for both Hiroshima and Nagasaki at 4 to 6 psi were 0.6 to 0.8; however, for the lower yield air bursts, the thermal radiation at the range of these overpressures was less intense in these cities than it would be for the 5-MT yield detonation. Even so, the general picture obtained from use of the data from Hiroshima and Nagasaki is a valid one, namely, that the survival rates of sheltered people in the Grey Belt would be high, even including the possibility of the development of a conflagration in some parts of the belt similar to the fires that occurred in those two cities.

The total area of the DAMAGED area, for the 5-MT detonation, and neglecting the downwind portion of the area that joins the RADEP area, would be about 260 sq mi. The area of the Grey Belt within this portion of the DAMAGED area is then 130 sq mi, or about 50 percent of the DAMAGED area. In general, the fraction of the DAMAGED area that would be included within the Grey Belt increases with weapon-yield because the radius of the fire-ignition perimeter increases with weapon-yield slightly more rapidly than do the radii of the exposure dose contours in the upwind and crosswind directions near ground zero. The distance at which an overpressure of 4 to 6 psi would occur increases with weapon-yield about in the same way as does the 100 roentgen infinity dose contour. For an air burst, the Grey Belt (with the inner boundary defined by the 4 to 6 psi overpressure) would be a larger fraction of the DAMAGED area.

In a general way, the people in the Grey Belt would be exposed only to the thermal radiation, initial radiations, and blast phenomena from a land-surface detonation in much the same way as they would be to the effects of a high air burst. And, except for areas in which conflagrations may occur, the survivors in the belt would be free to conduct operations as soon as they could be organized in the transattack and/or postattack period. The width, or depth, of the Grey Belt for the 5-MT land surface detonation would be about 3 miles in the crosswind direction and almost 5 miles in the upwind direction.

In a nuclear war, where multiple detonations would most likely occur, the Grey Belt of one detonation could be (or become) located in a RADEP area from one or more detonations farther upwind. If the time differences in the detonations were small, the situation would be similar to being downwind instead of cross- or upwind from the nearer detonation. If the time differences were more than several hours, actions applicable to either the Grey Belt or RADEP areas could be taken during that time, depending on which detonation effect occurred first.

Another portion of the damaged area may also be defined; this portion is called the Black Zone. It is the region in which complete

destruction of all structures except the strongest of underground shelters would occur. This area could be defined, for a surface detonation, as the area enclosed by a radius about twice that of the crater radius (normally where the overpressure would be between about 300 and 400 psi). Another way of specifying the location of the outer boundary of the Black Zone would be to set its radius equal to the maximum radius of the fireball; that is, about where an overpressure of between 100 to 200 psi occurred. Unless special shelters were available, the 100-200 psi radius would probably best represent, in a rough way, the distance from ground zero at which the survival rate of humans in heavy buildings would go to zero. For a 5-MT yield land-surface detonation, this distance would be about 1 mile from ground zero.

In the region between the Black Zone and the Grey Belt there remains an area with the shape of a circular band, varying from about 2 to about 4 miles in width in the upwind and crosswind directions from ground zero for the 5-MT yield explosion. In this region, unshielded movements of survivors or others entering the area would be restricted for some time because of exposure to radiation from fallout. The radiation intensities would increase rapidly with distance from the inner boundary of the Grey Belt in the direction of the Black Zone. This region of both extensive physical damage and high radiation intensities is called the Red Band.

7.2.4 Countermeasure Action Options of Civil Defense Organizations

These options can be outlined in a general way for each of the three major areas, i.e., the FREE, RADEP and DAMAGED areas. Organizations in the least-affected areas, of course, have the greater number of alternatives. But, since no organization or area can be sure, prior to attack, that it would be in any one of the three areas, all organizations should plan for all options.

Organizations in the FREE area may:

1. Mobilize all national-recovery industries to increase the output of needed survival and recovery products.

2. Establish medical, health, and rehabilitation service reception centers near the boundaries of the RADEP and DAMAGED areas to receive, aid, feed, house, and employ people evacuated from the two affected areas.

3. Establish staging areas on the boundaries of the RADEP and DAMAGED areas and organize countermeasure action teams having supplies and equipment for employment within the two affected areas.

4. Organize and coordinate recovery operations within adjacent RADEP and DAMAGED areas as well as with other FREE areas.

Organizations in the RADEP area may:

1. Stay in sheltered locations until the radiation intensity at each location has decreased by decay to a level at which short-term outside operations can be conducted; in the interim, radiological assessment data could be obtained and recovery plans and schedules could be reviewed and evaluated.

2. Organize and carry out radiological and economic recovery countermeasures for the RADEP area.

3. Organize evacuation movements of people to the FREE area or to staging areas within the RADEP area or on its perimeter.

Organizations in the DAMAGED area may:

1. Organize and conduct, in the Grey Belt, attack-phase and transattack countermeasure actions such as fire fighting, rescue, first aid, and emergency medical treatment.

2. At locations in the Red Band, organized survivors should stay in shelter until the radiation intensity at each location has decreased by decay to a level at which short-term operations can be conducted (or until large-scale fires have died down) and then evacuate to the Grey Belt and the FREE area.

3. Establish emergency, field-type medical, health, and rehabilitation service reception centers at the inner boundary of the Grey Belt to provide assistance to survivors evacuated from the Red Band.

4. Organize evacuation movements of people to the FREE area or to staging areas.

Some of the factors, besides the availability of sheltered locations for the population, that would determine whether a given action option could be undertaken are: (1) the type and degree of competence of the organization command and control structure; (2) the availability of people who know how to set up and direct any one of the countermeasures actions; (3) the availability of and access to surviving supplies and equipment, food, and other resources; and (4) the availability of operational-type plans for carrying out any of the

action options by all governmental (civil defense) organization units, from local to national levels.

Several features of the action options may be pointed out, viewing them all together. Most of the initial countermeasure actions after an attack would take place in the FREE area and in the Grey Belt of the DAMAGED area. Operations originating in the FREE area should tend to converge on the periphery of the RADEP area and the DAMAGED area. These initial activities in the Grey Belt would be more demanding because of the presence of physically injured survivors and fires. Some of the operations from the FREE area, when organized, could begin penetrating farther into the RADEP area and into the Red Band region as the radiation intensity decreases. After a few days, some of the organized groups in the RADEP area could emerge from shelter and start radiological recovery efforts on their own (where appropriate schedules, equipment, and supplies are available). In this way, clean staging areas could be formed and many could grow into islands of habitable decontaminated areas. These clean areas would finally merge as the occupants recovered more and more of their resources and facilities.

At the same time people would be emerging from the Red Band region of the DAMAGED area. In the initial stages of postattack recovery the Red Band and Black Zone regions would be completely evacuated. Possible use of the Red Band region would be for appropriation of heavy undamaged equipment and for waste disposal.

In certain types of attacks, the FREE areas in some parts of any country would be nonexistent for many miles in all directions and for several days after attack. In regions of the country (such as part of the midwest and eastern sections) where this could occur, the total number of action options would be decreased; in such areas, selected action options should be emphasized in the planning and in the organizing of the applicable countermeasures operations.

A well-coordinated assault on the early survival problems that could result from a large nuclear attack and use of the listed action options in the conduct of civil defense operations would be much like a huge military campaign. The organization and conduct of a military assault such as the landings in Europe and elsewhere in World War II can be compared in many ways with the way recovery efforts must be organized and conducted. The details of the operations would be different but their organization and logistics would have many similarities; they would all involve the directed use of surviving manpower, equipment, and supplies for doing many things simultaneously and under stress.

The most significant conclusion derived from the list of action options is that none of them is a "do-it-yourself" type. They are a large-scale operations involving coordinated actions by large groups of people. For

example, the rapid decontamination of a large enough area to make the effort effective would require crews and teams of people with various skills as well as several types of equipment. This general large-scale characteristic of the transattack and postattack recovery countermeasures is given in more detail, in the following paragraphs, by the highlight summary of some of the major countermeasure actions that may be taken by organized local groups.

7.2.5 RADEP Area Countermeasures

The primary countermeasure by which initial survival can be assured in the RADEP area is the provision of shielding for sheltering people from the external (gamma) nuclear radiations from fallout. The general requirements for shelter shielding can be derived from studies of the fallout levels that could occur in various types of assumed attacks on the U.S. Attack levels of 5,000 to 20,000 megatons could produce enough fallout to cover a very large fraction of this country with fallout levels equivalent to 500 r/hr at 1 hr. A lesser but still fairly large fraction of the country could receive levels of at least 5,000 r/hr at 1 hr; and a still lesser but significant fraction could receive fallout levels of 50,000 r/hr at 1 hr. At the higher end of the scale of attack levels, surface bursts of 5 to 20-MT yield weapons (50 percent fission) on hardened missile sites could result in fallout levels of 50,000 r/hr (and higher) over many of the midwest states, much of which is farm land. Fallout levels between 5,000 and 50,000 r/hr at 1 hr could be common in some of the eastern states.

For weapons in the yield range of 5 to 20 megatons, the maximum exposure dose occurs at locations where the fallout arrival time (in the RADEP areas) would be between 1 and 3 hours after detonation. For a mean arrival time of 2 hours, the infinity exposure dose for the 50,000 r/hr at 1 hr would be about 209,000 roentgens. Of this amount, about 164,000 roentgens would be delivered in two weeks, and 45,000 roentgens would be delivered after two weeks. At this fallout level, more than half the occupants of shelters having shielding factors of about 350 to 400 would be expected to die from exposure to gamma radiations. A shielding factor of 2,000 would be required to keep radiation exposures to about 100 roentgens in two weeks; the exposure dose in two weeks, for a shielding factor of 1000, would be about 160 roentgens. The true time-scale for these doses and shielding factors would depend on the time-period of attack; the infinity doses are independent of the time-scale of the attack.

The implication of these possible levels of radiation exposure doses that could occur in future attacks is that rather high performance and effective shelters would be needed to assure survival (from fallout only) of the population in certain parts of the country. In the RADEP areas where the fallout levels of 5,000 and 500 r/hr at 1 hr occurred, the exposure doses and acceptable shelter shielding factors would be less than for the 50,000 r/hr at 1 hr level by a factor

of 10 and 100, respectively. Thus, at the 500 r/hr at 1 hr level, a shielding factor of about 20 would result in an exposure dose of about 100 roentgens during a two weeks' stay time in shelter.

The above discussion suggests that the areas within the RADEP area in which the shielding factors of available shelters are less than a stated value could be marked off as Black Zones (same as the area around ground zero) if the level of fallout in those areas were above a stated amount. However, after the radiation levels decreased by decay, people from the FREE area or people who were in better shelters could recover equipment and supplies, decontaminate the area, and finally occupy it. The original occupants of the inadequate shelters in these areas would die within a few weeks from overexposure to radiation.

Rapid large-area decontamination, as the first step in the recovery of facilities and habitable areas in the RADEP area requires the use of manpower, equipment, and supplies. With adequate shelter, advance training, and good planning, the occupants of the RADEP area would, in many cases, be able to recover most needed facilities without direct help from the people in the FREE area. The initial recovery work would have to be done by organized crews and teams, not by individuals. The initial work would involve perhaps as much as 2 to 4 percent of the people of the RADEP area but might involve as much as 30 to 50 percent of the occupants before a satisfactory percentage of the RADEP area could be recovered. The recovery crew members and teams that initiate the recovery work should be in or come from the best shelters in the area, both to minimize their exposure and to decrease the time for initiating the recovery effort.

Data and methods exist for estimating the effort, effectiveness, and the time-scale of conducting radiological recovery operations. In general, organized recovery operations could be initiated as early as 3 to 5 days after the last detonation (which produces fallout landing on an area) in areas where the sum of the standard (H+1 hr) intensities from all contributing weapons is between 1,000 and 5,000 r/hr at 1 hr. Staging areas of the type suggested above could be established in working times varying from 3 or 4 hours to several days, depending on the types of surfaces in the area, the amount and type of available equipment, and the trained manpower available for the initial crew(s).

With some exceptions, the rural areas would predominantly lie in either the RADEP or FREE areas after a nuclear attack on the country. Therefore, most farmers would have one hour or more before fallout began arriving. In some areas it would therefore be possible for several farmers to have a group shelter which they would all have time to go to even after an upwind detonation occurred. Organized group recovery actions afterwards would generally not be possible in rural areas. On the other hand, most farmers

have motorized equipment that could be used to decontaminate land areas around houses, barns, and other buildings. Because of this, the farmer, if he has available shelter and food supplies for several weeks, could initiate recovery actions on his own initiative much more readily than the city dweller. The key element in the survival and recovery process in rural areas would be the availability of a good shelter.

Many of the long-term recovery problems and ecological consequences of a nuclear war will depend on the resolution of the radiological hazard in the rural areas where food is produced. The picture of the general situations for this subject area is still not clear; however, there appears to be little doubt that, for a heavy attack on the country, land contamination and ecological effects would have some, presently unspecified, significant role in the nation's postattack recovery process.

The available technical data on radiological recovery countermeasures, discussed in the following chapters, was used as a basis for many of the comments made in this section. Most of the comments are repeated in one form or another in the technical discussions. This introduction of the subject has been given within the scope of the many problems that a complete nuclear war countermeasure system or organization should consider mainly to set forth the role and place of the recovery countermeasures within the system.

7.2.6 DAMAGED Area Countermeasures

The major protective countermeasure in the DAMAGED area during the attack phase is shelter. Many people in buildings and in so-called "fallout" shelters, as previously discussed, would survive from the thermal radiation and blast phenomena in the Grey Belt. For protection against these two phenomena and also against the initial radiations in the Red Band, the shelters would have to be designed to withstand blast overpressures up to about 100 psi and should be buried to a depth of about 10 feet underground. Protection in the Black Zone would require shelter burial depths of 20 to several hundred feet. Since warning of attack could come in many ways just as a war could develop in many ways, no a priori connection between a special type of warning system and blast-shelter effectiveness can be established on technical grounds, except for the special case of a hypothetical surprise attack.

The only initial practical major transattack and postattack countermeasure for the Red Band and the Black Zone (if any survivors are left in the latter) is evacuation to the Grey Belt as soon as the radiation is low enough to permit movement. In the Red Band, the time of fallout arrival would be between about 20 and 30 minutes for detonations in the 5 to 20 megaton yield

range. Thus, if it is assumed that a second explosion would not occur in the same area within that time period, survivors in shelters could go outdoors and carry out brief rescue operations near the shelter. Evacuation of the slightly injured and uninjured from the peripheral areas would be a possible option. Emergency medical treatment of the injured (rescued) people in shelter would be an alternative countermeasure. Another, previously mentioned, is the appropriation of undamaged parts of equipment and facilities. Debris clearance operations may be required in the postattack period to evacuate people from shelters. In the Red Band, fire fighting should not, in general, be attempted.

Many transattack countermeasures would be feasible for use in the Grey Belt region. After the blast wave had passed and the observed damage effects had indicated to local authorities or to the occupants of a shelter (or house, etc.) that they were in the Grey Belt, the uninjured survivors could proceed to put out incipient fires, organize fire fighting operations at priority locations (predesignated as they would have to be for recovery in a RADEP area), conduct rescue operations, set up first aid stations and emergency hospitals, and initiate all other transattack countermeasures. The degree to which the many countermeasures could be initiated and carried out in the Grey Belt would depend almost entirely on the success the uninjured survivors had in dealing with the ignited fires. Thus in this area, fighting the fires promptly would have a first priority of importance over all other actions. This order of priority would hold even if all the occupants had fire-proof shelters; that is, it would hold for all the people in the areas not enveloped by a conflagration or firestorm which might develop in some parts of the Grey Belt.

The duration of urgent fire fighting and rescue operations in the Grey Belt would be about two days. After this time the survivors, with help from the civil defense organizations in FREE areas in the upwind and crosswind directions from the detonation(s) (if these FREE areas are available) could organize operations to assist the surviving people who are evacuated from the Red Band region of destruction.

Within the first two days after attack, postattack damage repair countermeasure operations could be organized at the outer periphery of the DAMAGED area and the Grey Belt. These operations could proceed from areas of lightest damage and work inward towards the Red Band. In the initial repair operations, designated priority facilities would be repaired first. The repair of other facilities and factories would follow at a less urgent rate. In areas of the Grey Belt where large amounts of debris were present, debris clearance operations would precede the damage repair crews. Disposal and/or burial of the dead--especially flash burn victims who were outside and exposed directly to the thermal radiation in the Grey Belt and Red Band at the time of detonation--would be undertaken early as one of the transattack cleanup operations in these areas.

In the portion of the Grey Belt adjoining the RADEP area directly downwind from ground zero, no transattack operations would be possible because of high radiation intensities from the fallout. However, for people in fireproof shelters, the previously described RADEP countermeasures would be available. If all useful facilities were destroyed by the fire, survivors should move to a cleaned region of the adjacent RADEP area or to an adjacent FREE area.

7.3 The Protection Factor Concept

The basic assumption about an over-all nuclear war countermeasure system is that its first function is to save lives during an attack. Reducing damage to property, sustaining the survivors, and other such measures are secondary; they can be given some order of importance pending the outcome of the first function.

If the relative effectiveness of any combination of countermeasure functions, or actions, can be represented by a system protection factor, PF_j, then a general statement can be made about the basic nature and intent of a countermeasure system. The substantive arguments pertinent to this statement may be derived from the relationships between the detonation phenomena and the meaning of the system protection factor in terms of survival.

First, for each of the separate phenomena of a nuclear explosion, it may be stated that more people would survive if they used countermeasures with a protection factor of two than if they used countermeasures with a protection factor value of one. Also, more people would survive if their protection factor is four rather than two, and so on. Therefore, if this relationship among the number of survivors, the protection factor, and the phenomena holds for each of the explosion phenomena, it must apply to all the explosion phenomena in a single detonation, as well as to the multiple detonations possible in a nuclear war. In other words, the effective perimeters of the affected areas, with respect to survival, decrease as the value of the protection factor of the countermeasure system increases.

Since the countermeasure system objective is to save as many lives as possible, the system must be designed to maximize, at any point in time, the sum of the products of $N_j PF_j$, where N_j is the number of people having available countermeasures with a given protection factor, PF_j. Hence, the distribution of the countermeasures with a range of PF_j values relative to the population distribution must be considered in the design and development of the system. Thus the basic nature and intent of any countermeasure system, including its various subsystem, is to organize protective and countermeasure functions in such a way as to maximize the sum of the products of $N_j PF_j$, at any

point in time; i.e , to save the maximum number of people possible with the available countermeasure system.

The value of N_j may be increased simply by including more people within the system; this may be done by providing more people with the means of protection and by including more of the people in the system organization. The value of PF_j may be increased by improving the effectiveness of the system components such as shelter and decontamination methods. Of course, if only a few people have available countermeasures with high PF_j values and many people have available countermeasures with low PF_j values, the sum of the products of N_j PF_j would probably not be maximized.

In a system that utilizes whatever protection is available instead of being designed and built to specification, the emphasis of system composition must be on having, at all times, the best protection available for all the people. This type of system cannot establish protection standards and it must consider use of system components with decreasing PF_j values until all people are included in the system. If this were done, then for any given nuclear attack, the result of maximizing the product of N_j and PF_j would be to maximize the number of survivors (and perhaps the amount of non-human resources).

7.4 Objectives of Radiological Countermeasures

The radiological hazard from fallout is characterized by the accumulation of exposure dosage over a period of time; therefore, the specific objective of any radiological countermeasure is to reduce to a stated level the exposure dose from radioactive sources in fallout. In a broad sense, the objective of a series of radiological countermeasures or of their systematic use, in the case of nuclear attack, would be to preserve the society of the survivors as an organized operating entity for the future.

A system of countermeasures based upon such a broad objective would include countermeasures whose sole purpose is to save lives, countermeasures whose purpose is to regain the earliest possible use of contaminated (and perhaps damaged) utilities, factories, farms and other resources necessary for maintaining the livelihood of the human survivors, and countermeasures for controlling the incorporation of long-lived radioelements into the human body.

Specification of the kinds of radiological countermeasures and their effectiveness in meeting the requirements of both their broad and specific objectives can be made only in terms of the nature of the radiological hazard itself together with prescribed limitations on exposure dosage.

The rate of delivery of the exposure dose follows curves similar to those of Figures 5.9 and 5.12. The ionization rate is shown to increase rapidly with onset of fallout, to pass through a maximum before or near the time when fallout ceases to arrive, and then to decrease because of radioactive decay. The exposure doses for the curve of Figure 5.9, for 35 miles downwind from the 1-MT yield detonation, can be used to illustrate how this characteristic delivery of dosage may occur. The accumulated exposure dose for this location is shown in Table 7.1 from the arrival time of fallout up to 2 years (at which time the gamma radiation has decayed almost to background levels). The exposure times for exposure doses of 30 and 75 roentgens and the average incremental dose per hour are included to illustrate the characteristic change in dose delivery with time due to decay. The very rapid dose delivery at the early times after detonation and decreasing rate of delivery with time suggest that a passive type of countermeasure (i.e., protective shelter) would be most applicable at early times and that, after some time, active types of countermeasures could be initiated.

Because the dosage is delivered so rapidly at first and because the doses delivered are in excess of lethal amount in areas where heavy fallout occurs, the passive type countermeasures must be concerned with survival itself. The period of time over which they must be used is called the shelter and attack phase or Emergency Period.[1] The necessity for active type countermeasures may arise from a desire to shorten the period over which the passive type countermeasures are used, a requirement for accomplishing a needed task or mission by a certain time, or by the desire to keep the exposure dose to people within a low value over an extended period.

For example, if 30r per day and 1,000r per year are taken as the (desired) upper limits of the exposure dose, then for the situation described in Table 7.1, the passive countermeasure must be capable of reducing the 3,600r dose in the first day to 30r--i.e., it must reduce the exposure dose by a factor of 120. If the same rule holds at later times then an outside (of shelter) exposure on a continuing basis would not be possible until after 24 days in shelter. With a shelter attenuation factor of 120 and outside exposures after the 24th day, the dose received by the 25th day would be about 90 roentgens. From the 25th day to 1 year, the dose received would be 8370 less 6800 or 1570 roentgens and the total exposure dose would be about 1700 roentgens.

Because of such a large exposure dose over a year's time, an active countermeasure would be required in addition to the shelter if the desired dose limits are not to be exceeded. Such countermeasures would certainly be desired to shorten the emergency period to less than the 24 days' stay-time in shelter. Because many requirements for operations of one type or another would occur in event of nuclear attack, the major requirement for active countermeasures

would undoubtedly arise from this source. The period of time during which all types of operations are to be re-established is called the initial Recovery Period.

All of the countermeasures during the Emergency and Recovery Periods have as a major requirement the reduction of exposure dose due to gamma radiations. However, after one year or so, the gamma radiation will have decayed away leaving only the long-lived radionuclides. These may constitute an ingestion hazard by their incorporation in the food chain and subsequently concentrating in body organs.

While the predominating radiological hazard would shift to an internal one at about a year, the initiation of this hazard would begin sooner and should involve exposure control type countermeasures as soon as the recovery period from the gamma hazard is finished or well under way. Because countermeasures for the internal hazard should deal with elimination of long-lived nuclides from the biosphere, the period of time over which they may be required will be called the Biological Elimination Period. These countermeasures may be required for several years after a nuclear war.

7.5 Emergency Period Countermeasures

Two major types of radiological countermeasures may be considered applicable to the emergency period. These are shelter, or shielding, and dispersal. Dispersal would not be expected to be as effective a radiological countermeasure as shelter since it does not reduce the exposure dose at a given location. It's use could reduce the exposure dose of some people by virtue of an appropriate selection of locations where the exposure dose itself might be low or by spreading the population over a larger area. Intrinsically, however, dispersal combined with shelter would provide more over-all protection against blast and thermal effects of a detonation.

The major characteristic of shelter or shielding that is of interest here is its use in the attenuation of the gamma radiation, and in the relationships among the shielding effectiveness of a shelter, the duration of the emergency period, and the effectiveness of recovery period countermeasures. The habitability aspects of shelter, including food, water, ventilation, and so forth, are not considered here. Many documents that treat these subjects are available from local civil defense organizations and other government agencies; References 2, 3, and 4 contain information covering these subjects.

Table 7.1

ACCUMULATED DOSE AND EXPOSURE TIMES FOR EXPOSURE DOSES OF 30r AND 75r AT 35 MILES DOWNWIND FROM A 1-MT YIELD FISSION WEAPON WHERE I(1) = 2000 R/HR AT 1 HR

Time After Detonation	Exposure Dose in Roentgens	Exposure Time for 30r	Exposure Time for 75r	Average Incremental Dose in r per Hour
1.9 hr	0	--	--	--
2.4 hr	87	--	--	174
2.9 hr	326	--	--	478
4 hr	846	3.6 min	11 min	472
6 hr	1500	6 min	17 min	327
8 hr	1950	9 min	24 min	225
12 hr	2580	16 min	36 min	158
1 da	3570	30 min	1.3 hr	82
2 da	4530	1 hr	3 hr	40
3 da	5050	2 hr	4.5 hr	22
4 da	5400	3 hr	6.5 hr	15
1 wk	6060	7 hr	16 hr	9
2 wk	6560	14 hr	1.5 da	3
1 mo	7060	1.5 da	3.5 da	1.3
3 mo	7720	4 da	12 da	<1
6 mo	8120	11 da	32 da	<1
1 yr	8370	81 da	∞	<1
2 yr	8460	∞	∞	<1

7.6 Recovery Period Countermeasures

Recovery countermeasures are active countermeasures in the sense that they involve positive efforts to reduce the gamma radiation after the fallout has been deposited. These countermeasures include removing the fallout from surfaces and putting it at waste disposal sites, burying the particles under the soil on which it rests to obtain a reduction in the radiation due to shielding by the soil, and by constructing temporary shielding with sand bags, piles of earth, or with other dense material.

Since removal of the fallout by decontamination would usually be the most effective of the recovery period countermeasures, it is discussed in detail in the following chapters. When prompt recovery of vital facilities and areas is important, recovery operations should start as soon as possible. In such cases there generally are important relationships among the effectiveness of the shelter, the effectiveness of the recovery procedures, the dose allotted to recovery crews, the time after attack when the recovery operation can be initiated, and the initial level of the deposited fallout.

The effectiveness of decontamination of fallout can depend very heavily on the reactions between the chemical constituents of the fallout and the surfaces it reaches. The nature of the fallout and its composition, as discussed in previous chapters (see Volume I), can be used to provide the necessary estimates of what chemical system must be considered in decontamination, what its reactions may be with surfaces, and what chemical and physical means are available for removing the fallout, or its radioactive components, from surfaces. In addition to the chemistry of the processes, consideration must be given the large-scale engineering and operational aspects of removing fallout from exposed surface.

7.7 Biological Elimination Period Countermeasures

The lack of comprehensive studies that could provide realistic estimates of the hazard levels of the long-lived radioelements prevents treatment of the possible or required countermeasures for this period in the same frame of reference as for the gamma radiation hazards from fallout. Although applicable data exist on the uptake and biological effects of internal emitters on both plants and animals, only recently have studies been initiated on the relationships between the likely availability of radioelements in fallout and their biological effect. The main concern in these relationships is centered on the entry of radioactive elements in the food chain from plants and animals to humans. Because of the current lack of definition of both the actual hazard level that may occur in a nuclear war and the methods for specifying countermeasure requirements for this hazard, no further discussion is given on biological elimination countermeasures in this report.

CHAPTER 7 REFERENCES

1. The Radiological Recovery of Fixed Military Installations, NAVDOCKS TP-PL-13, revised (1958)

2. Strope, W. E., L. G. Porteous, A. L. Greig, Specifications and Costs of A Standardized Series of Fallout Shelters, USNRDL-TR-366 (1959)

3. Proceedings of the Meeting on Environmental Engineering in Protective Shelters, National Academy of Sciences--National Research Council, Washington, D.C. (1960)

4. Cannell, Rogers S., LIVE: Plan to Survive a Nuclear Attack, Prentice-Hall, New York, N.Y. (1961)

Chapter 8

INTERACTIONS OF SUBSTANCES IN FALLOUT WITH SURFACES AND THEIR BEHAVIOR IN DECONTAMINATION PROCEDURES

8.1 Factors Influencing Fallout Contamination and Decontamination Behavior

8.1.1 Information Needed for the Study of Decontamination Processes

Before meaningful studies and investigations on the problem of fallout decontamination can be conducted, and to understand, work on, and cope with fallout contamination problems certain basic data and information on the properties and behavior of fallout must be accumulated. These include knowledge of the physics and chemistry of the fallout material, its reactions with exposed surfaces, and its behavior in decontamination procedures. Some of the kinds of information required for quantitative investigations of decontamination processes are:

1. The composition and properties of the environmental carrier material that transports the radioactive elements.

2. The number and kinds of radioactive elements that contribute to the radioactivity of the fallout material.

3. The amount and kind of nonradioactive materials from the device or weapon.

4. The surface density of radioactive material that is deposited on a surface creating a given gamma radiation intensity.

5. The manner of fallout deposition on a given surface.

6. The kinds and types of materials likely to be contaminated.

7. The time of decontamination relative to the time of detonation and to the time of surface contamination.

8. Likely atmospheric conditions between the time of detonation and/or contamination and decontamination.

9. A description of the decontamination method (its mode of action on the fallout material, rate of reaction and application, etc.).

8.1.2 Effect of Environmental Carrier Materials on Decontamination

The composition and properties of the fallout carrier material will largely control the reactions that the radioactive constituents will have with a surface. If the radioactive elements are inside fused glass particles, as they are for most of the larger fallout particles from near-surface detonations collected at the Nevada Test Site, they cannot react directly with a surface. Only the particles themselves interact with surfaces, and a decontamination method that removes the particles also removes the radioactivity.

If the fallout from a detonation on or in deep water arrives at a surface in a liquid (rain), or as wet crystalline agglomerates in which many of the radioactive elements are present in the ionic form, the various radioactive elements can directly react with a surface material. In this case, a decontamination method must act upon each element or ion on an individual basis. Other types of fallout could exhibit behaviors, in decontamination, that are intermediate between those of the large particles and the small ions.

Besides determining the behavior of the radioactive constituents, the properties of various possible carrier materials must be determined before the fallout can be characterized as a chemical system.

In terms of mass, fallout is land surface composed essentially of the carrier material (soil, seawater residue, etc.). For example, a one-MT yield detonation of 100 percent fission would produce about 100 pounds of fission products and would inject about a million tons of soil into the atmosphere. These and other types of quantitative information on the composition of fallout can only be obtained from analyses of the fallout produced in field test experiments of nuclear weapons.

8.1.3 Radioactive Constituents

The number and kinds of radioactive elements that may be present in the fallout from fission weapons are generally well-known. While the radioactive nuclide composition of the fallout varies with time after detonation, the composition of the radionuclides present at a given time determines the characteristics of the gamma and X-radiations that are emitted. Differences in the radioactive nuclide composition of fallout will result in differences in the energy distribution of the gamma and X-radiations as well as in the gross decay rate of the mixture(s) of radionuclides.

The radioactive composition data used in much of the experimental work presented in this chapter was based on W.J. Heiman's [1] original calculations of the contributions of various elements to the gamma radiation rate at various

times from 1 hour to 3 years after detonation of a fission weapon. According to Heiman's calculations, 85 percent or more of the total gamma radiation, at any time in the stated time interval after detonation, consists of radiations from only 12 elements, namely, Cs, Sr, Y, La, Ce, Pr, Zr, Nb, Te, Ru, I, and Np. Later calculations[2,3] have confirmed the relative importance of these elements. Quantitative data that describe the behavior of these elements in various fallout materials are needed for making quantitative evaluations of decontamination processes.

8.1.4 Materials Contributed by the Warhead, Bomb, or Target

The amounts and kinds of nonradioactive materials in a bomb or in the warhead of a missile, and the radioactive composition and environmental materials, together determine the gross composition of the fallout produced in a detonation. The deposition of the fallout on a surface results in a contaminated system; that is, a surface on which fallout has been deposited is termed a contaminated surface.

8.1.5 Influence of Deposition on Decontamination

The manner in which fallout is deposited on a surface can influence its contamination potential. Some of the deposition parameters are: (1) surface orientation, (2) surface type, (3) type of fallout, and (4) weather conditions. Data and information on the mechanics of fallout deposition are needed in evaluations of the radiological hazard for different types of target complexes and in the planning and scheduling of large-scale decontamination operations. They are also needed in designing decontamination-method testing experiments. The data can be obtained through field tests of nuclear weapons or through laboratory experiments using synthetic fallout materials.

8.1.6 Effect of Surface Materials on Decontamination

The kinds of surface materials most likely to be contaminated by fallout in a nuclear war can be determined from surveys of the target areas and facilities which, if contaminated, would be reclaimed. Much of the experimental data that are presented in this chapter were obtained from test surfaces of Navy gray paint; the prominence of available data for this surface reflects the emphasis, in decontamination research, on the problems of contamination of ships by fallout from nuclear detonations in a seawater environment. For investigating contamination by land or harbor detonations, studies of the decontamination of concrete, surface asphalt, surface roofing materials, and unpaved surfaces would be more appropriate.

8.1.7 Effect of Time on Decontamination

Time is a parameter in decontamination because of both radioactive decay and the effect of time itself on the effectiveness of some decontamination procedures. Fractionation of the radioelements in the decontamination process itself, for certain types of fallout and decontamination methods, depends on the age of the fallout. In addition, aging of the fallout material can cause changes in the nature of the bondings to a surface. Oxidation, dehydration, evaporation, crystallization, corrosion, etc., are a few of the possible processes that could influence the effectiveness of decontamination procedures over a period of time, depending on the rate at which the process took place.

8.1.8 Effect of Atmospheric Conditions

For some types of fallout the atmospheric conditions that prevail between the time of detonation and/or contamination and the time of decontamination can determine the nature of the interactions of the fallout with the surface on which it is deposited. Humidity, rain, temperature, and wind are influential parameters (see Chapter 2). The rate of drying of a liquid type of fallout, for example, has been found to change its contamination potential.

8.1.9 Effect of the Decontamination Method

In experimental tests of decontamination methods, the objective often is to evaluate the effectiveness of the method as a single procedure. A method, if complicated, could have many adjustable parameters. For example, each of the dry methods, such as sweeping, vacuuming, brushing, and sand blasting, has a set of operating conditions that results in a given decontamination effectiveness with respect to a set of working time, equipment, and manpower requirements. Also, each of the wet methods, such as firehosing, jet spraying, and scrubbing, has its adjustable operational parameters; these include the advantage, if any, of using soaps, detergents, or other chemical additives.

Certain decontamination methods can be used to investigate the surface reactions of the fallout constituents. The water immersion stirrer method, in which a surface is flooded with slow-moving water, for example, minimizes physical forces in the removal process so that absorption and other chemical reactions can be measured. For much of the data in the following pages, the details of the procedures used in the decontamination methods are not given but are available in the cited reports.

8.2 Fallout from Detonations on Land

8.2.1 General Concepts

The essential characteristics of fallout from land surface detonations that are important considerations in decontamination are: (1) the fallout consists of solid particles; (2) the radioactive elements are fused into, or condensed on, the surfaces of these particles; and (3) removal of the particles assures removal of the radioactive elements they carry.

Except for very high melting soils, a large fraction of the radioactive elements in the fallout, where the radiation levels are high enough to require decontamination, will be fused into the fairly large melted spheroidal (glassy-bead) soil particles. Most of the larger irregular particles, carrying the more volatile radioelements on their surfaces, will have lower specific activities than the fused glassy-bead type.

Although it is possible that decontamination methods may leach out some of the radioelements condensed on the surfaces of the particles, this has never been observed to be a problem when the decontamination operation proceeds with movement of the mass of particles and water to a suitable drainage system. The general effectiveness of such methods could be reduced if the particles were merely wetted in place and allowed to dry; in this case the elements adsorbed on the particle surfaces might be dissolved, transferred to surfaces on which the particles rest, and become chemisorbed onto those surfaces. This possibility is not considered further in discussions of the decontamination behavior of land fallout. The main emphasis in the treatment of land fallout is on the decontamination of the larger particles by use of procedures that can be applied at fairly high operational rates.

Because the decontamination of fallout from land surface detonations can be described in terms of particle-removal and particle-transport mechanics, the requirements for data on the chemistry of both the interactions of the fallout with surfaces during deposition and the interactions during application of the cleaning procedures are not very large.

8.2.2 Interactions of Particles with Surfaces

No important short-range forces or interactions between the larger fallout particles and exposed surfaces occur during or after the deposition of the fallout. For particles with diameters greater than about a micron, the only force of importance in their removal is that of gravity. As they fall and accumulate on areas, under the influence of localized airflow patterns, the particles tend to fall into cracks or crevices and into the local minute depressions of all surfaces.

For the higher levels of fallout deposition, the surface density of particles may be sufficient to cover a surface with more than one layer of particles.

To describe the gross features of the contamination process that influence the effectiveness of a decontamination method, a reasonably smooth surface (such as smooth concrete pavement) is assumed. Since work must be applied to remove the fallout particles from a surface, the mass surface-density of the particles is the most important single interaction parameter that requires definition. Because work in decontamination is applied to a surface as a whole, but may be effective in overcoming gravity forces on the particles covering only portions of the area of a surface, a relationship between the fraction of the area covered and the mass surface-density of the particles is needed to describe how the removal effectiveness (for a given amount of work) depends on the mass surface-density.

If the probability of a particle's arriving and landing in a clean part of the area, as the fallout deposition on a given area progresses, is proportional to the fraction of clean area available, then the increase in the fraction of the area covered by particles at any time is proportional to the amount of clean area available. This can be written as

$$\frac{df}{dy} = k_f (1 - f) \tag{8.1}$$

in which f is the fraction of the area covered by particles, y is the average mass surface-density of the particles, and k_f is a constant for a given particle size group, surface roughness, and particle density. Integration of Eq. 8.1 from $f = y = 0$ to their final values gives

$$f = 1 - e^{-k_f y} \tag{8.2}$$

The form of Eq. 8.2 specifies the manner in which the fraction of the area is covered with particles as the mass surface-density increases. The value of k_f should be a measure of the available holes and minor roughness features of the surface with respect to the size of the particles.

8.2.3 Decontamination Equations for a Single Size-Group of Particles

If the assumed smooth surface is covered with several layers of particles of a rather narrow size distribution, and the particles are removed by a method that picks up or accelerates all particles that are not touching the surface, as well as all particles larger than a given size that actually rest on the

surface, then a given number will be left on the surface (depending on the number-size distribution of the particles). In practice, this condition might be achieved by passing a grader bar over the surface, by sweeping the surface many times, or even by flowing a film of water over the surface many times. The amount of particles remaining on the surface, after sweeping with a broom many times, might be controlled by the number and size of the minor depressions from which the smaller particles are not removed.

In laboratory experiments the minimum number of particles not removed from a surface might be attained by flowing water over the contaminated surface for some time, or by suspending a sample surface vertically in water so that gravity and surface tension forces can act to remove all the larger particles. In each of these cases, the minimum number of particles remaining on the surface, starting with a saturated surface (one or more layers of particles) and expending an excess of effort or of decontamination solutions, should be a number characteristic of the surface and the method. This number, in terms of the mass of the particles per unit area, is designated R_M.

Ideally, the number should also depend on the number-size distribution of the particles; however, in practice most methods will smear out the particles so that the smaller particles not originally in contact with the surface can fall into crevices vacated by larger particles. Therefore it is more realistic to consider the value of R_M as being dependent on the mean particle size of the distribution rather than on the actual form of the particle-size-number-distribution. For surfaces with fractional coverages less than unity, the first estimate of the mass of particles remaining is $R_M f_j$ or

$$R_m = R_M (1 - e^{-k_f y}) \text{ (mass/unit area)} \tag{8.3}$$

Some smearing of the distributions on fractional surface coverages also will occur upon application of a decontamination method. But where k_f is determined from decontamination data, it will contain the effects of the smearing and therefore k_f, determined this way, will depend on the decontamination method as well as on the surface type and density of the particles.

The general predictive result of Eq. 8.3 is that the mass remaining increases with the deposit level y until $\exp(-k_f y)$ becomes small with respect to unity and thereafter remains constant and equal to R_M. In Chapter 9, the final level, R_m, is called the infinite effort remaining mass level and should be the minimum mass level remaining that can be obtained by application of a decontamination procedure many times or with a very large expenditure of effort.

The values R_m can be converted to radiation rates remaining as of H+1 by use of the mass contour ratio; thus

$$R_r(1) = \left[R_M / M_r(1)\right]\left[1 - \exp(-k_f M_r(1) I(1))\right] \quad \text{r/hr at 1 hr} \qquad (8.4)$$

It is often convenient to make all computations in terms of r/hr at H+1 and to convert the results to fractions remaining for use at other times after detonation. This procedure, however, can result in error when the decay curve is not the same for the remaining particles as it is for the initial deposit. In such cases, a new decay curve is required to estimate the dose rate from the remaining particles.

For a smooth plane and hexagonal close-packing of spheres of density 2.5 gm/cm^3, a single layer of particles of a given size would have the mass surface-density

$$m_x(\max) = 140\ d(\mu)\ \text{mg/sq ft} \qquad (8.5)$$

where $d(\mu)$ is the particle diameter in microns. Thus a layer of 100μ particles would have a surface density of 14 gm/sq ft. Equation 8.5 can be used to estimate the mass loading for surface saturation or, for a heavily loaded surface, to estimate the equivalent diameter of the remaining particles.

Data [4,5] for the decontamination of soils deposited as a slurry on Navy gray paint surfaces and then dried before decontamination are shown in Table 8.1. The surfaces were decontaminated by immersion in stirred water until they were thoroughly wetted and then drained by dipping, with the surface in a vertical orientation, in clean water. The particles masses were measured by weighing the plates before and after decontamination. The results are expressed in terms of the fraction of mass remaining, F_m, which is equal to R_m/y.

In another decontamination experiment,[4,6] Nevada Test Site dirt and clay soils were tagged with about 1 mc of Ce-144 by making a slurry of 100 grams of each soil in 500 millileters of water containing the tracer. The slurries were slowly evaporated down to dryness, oven-dried overnight, and fired at 900° C for one hour. Small portions of the fired material were washed with water. A count assay of the wash water showed that less than 0.1 percent of the Ce-144 was removed from the soil. Weighed sample-plates, one-inch square, coated with Navy gray paint, were contaminated with the soil by allowing it to fall through coarse screens.

After contamination, the plates were reweighed and counted with a gamma scintillation counter. The specific count rate thus obtained was used to convert all the counting data to mass data. Half of the samples contaminated with the tagged soils were placed in a high-humidity chamber for 12 hours and then oven-dried at 30°C for one hour. This set of samples was designated "prewet" soils.

A water-spray method and a water immersion stirrer method were used to decontaminate the test surfaces. In the spray (or hosing) method, the samples were exposed in a closed chamber to a spray of water applied through a fine nozzle at 50 psig for 30 seconds. In the stirring method, the samples were immersed in 250 millileters of water and gently stirred for 5 minutes; afterward they were rinsed in a vertical position in clean water to drain the loosened particles from the plate.

Table 8.1

DECONTAMINATION OF SOILS FROM NAVY GRAY PAINT SAMPLES BY THE IMMERSION STIRRER METHOD

San Francisco Harbor Bottom Soil			Clay Particles		
y (mg/sq ft)	F_m (observed) (percent)	F_m (calculated) (percent)	y (mg/sq ft)	F_m (observed) (percent)	F_m (calculated) (percent)
1,680	13.0±4.0	12.9	1,860	25±10	25.4
3,410	8.8±1.7	8.8	3,560	12±10	21.0
7,140	5.4±1.0	4.8	6,880	15±5	15.0
13,800	2.2±0.5	2.5	13,800	9.8±1	8.6
32,500	1.1±0.2	1.1	33,800	3.1±0.5	3.6

R_M = 350 mg/sq ft

k_f = 5.76×10^{-4} sq ft/mg

$d(\mu)$ = 2.5

R_M = 1200 mg/sq ft

k_f = 2.71×10^{-4} sq ft/mg

$d(\mu)$ = 8.6

The amount of soil remaining after decontamination was determined from the observed count rate and the specific count rate of the soil. Some error in the data results from this conversion because the tagging procedure would not result in a constant specific activity for all particle sizes; generally, the specific activity is larger for the smaller particles. Thus using the average value of the specific count-rate of the soil in computing the mass of the remaining particle should tend to give an over-estimate of the mass of smaller particles not removed during the process.

The data from the experiment are shown in Table 8.2. The masses remaining for the spray method (also the prewet clay soil for the stirrer) are not well represented by Eq. 8.3 but are quite well represented by an empirical equation of the form ay^n. Although the particle sizes of the soils are not reported, the clay soil used in this experiment was from a finer mix than that used in obtaining the data of Table 8.1. Since the clay in that experiment was actually slurried with water and then dried, the observed data suggest that Eq. 8.3 represents the decontamination results best for larger particles.

The form of the empirical equation representing the data for the high pressure water spray can be derived if it is assumed that: (1) the increase in the mass of the remaining small particles per unit increase in the mass surface loading is proportional to the fraction of these small particles present in the total mass deposited per unit area; and (2) the fraction of the small particles present is proportional to R_m/y. The combination of these two assumptions may be written as

$$\frac{dR_m}{dy} = \frac{nR_m}{y} \tag{8.6}$$

The relation integrates to give

$$R_m = ay^n, \quad R_m = 0 \text{ to } R_M, \text{ or } y \leq (R_M/a)^{1/n} \tag{8.7}$$

where a and n are constants whose values depend on the method, type of particles, the treatment or condition of the contaminated system, and, undoubtedly, on the type of surface. In each case, the concept of surface saturation is retained so that at sufficiently high mass loadings, the amount of particles not removed becomes constant. All the data show that R_m increases with y, at least at the lower values of y.

The data show that the physical forces in the impact of the high pressure spray to be an important factor in the removal of the particles. The improvement in decontamination due to the impact of the water over the decontamination by simple water washing, in the data of Table 8.2, was about a factor of 10 for the dry Nevada soils, about a factor of 4 for the prewet Nevada soil, about a factor of 15 for the dry clay soil, and about a factor of 4 for the prewet clay soil, considering the higher levels where R_M applies.

The prewetting of the soil tended to reduce the difference between the removal effectiveness of the two methods and most of the reduction in the difference in the effectiveness was due to the decrease in effectiveness of the

Table 8.2

DECONTAMINATION OF TAGGED SOIL PARTICLES FROM NAVY GRAY PAINT SURFACES*

Dry Nevada Soil			Prewet Nevada Soil			Dry Clay Soil			Prewet Clay Soil		
y	R_m (obs)	R_m (calc)	y	R_m (obs)	R_m (calc)	y	R_m (obs)	R_m (calc)	y	R_m (obs)	R_m (calc)
1. Immersion Stirrer											
71.6	7.95	4.5	104.	14.1	12.1	24.8	2.88	0.46	51.0	34.0	37.0
757.	57.8	44.8	142.	20.3	16.4	105.	3.31	2.04	59.6	40.0	38.6
931.	62.5	54.1	642.	63.5	65.2	131.	8.06	2.55	982.	83.5	82.0
2,000.	83.2	101.	990.	95.7	93.2	148.	6.91	2.86	983.	104.	84.2
2,320.	113.	113.	2,710.	92.2	181.	3,100.	48.0	46.1	3,890.	108.	124.
17,100.	308.	243.	16,700.	255.	(252)	5,980.	68.1	70.0	4,060.	115.	125.
17,400.	184.	244.	181,000.	222.	(252)	21,600.	107.	100.	11,900.	160.	168.
206,000.	245.	(246)**	216,000.	281.	(252)	161,000.	255.	(102)	130,000.	318.	327.
$R_M = 246$ mg/sq ft $k_f = 2.66 \times 10^{-4}$ sq ft/mg			$R_M = 252$ mg/sq ft $k_f = 4.67 \times 10^{-4}$ sq ft/mg			$R_M = 102$ mg/sq ft $k_f = 1.94 \times 10^{-4}$ sq ft/mg			$R_m = 12.4\ y^{0.278}$ mg/sq ft $R_M \sim 375$ mg/sq ft		
2. Spray Chamber											
34.8	0.348	0.32	98.2	3.46	3.99	119.	0.75	0.66	64.5	16.7	8.13
900.	2.59	1.65	178.	5.18	5.38	268.	0.75	0.88	74.3	8.92	8.56
2,850.	2.59	2.93	690.	12.7	10.6	3,860.	2.16	2.21	443.	15.7	15.9
3,110.	3.17	3.06	724.	12.1	11.1	4,640.	2.46	2.36	536.	19.0	17.0
12,800.	5.18	6.19	3,040.	22.0	22.2	23,600.	4.03	4.16	1,670.	16.7	25.2
17,600.	3.60	7.27	12,800.	48.4	45.6	29,700.	4.75	4.50	2,260.	24.2	28.0
204,000.	23.8	24.8	18,300.	45.8	54.5	177,000.	6.55	(6.6)	--	--	--
213,000.	25.2	(25)	178,000.	37.9	(60)	187,000.	6.55	(6.6)	--	--	--
$R_m = 0.0548\ y^{0.50}$ mg/sq ft $R_M \sim 25$ mg/sq ft			$R_m = 0.403\ y^{0.50}$ mg/sq ft $R_M \sim 60$ mg/sq ft			$R_m = 0.125\ y^{0.348}$ mg/sq ft $R_M \sim 6.6$ mg/sq ft			$R_m = 1.91\ y^{0.348}$ mg/sq ft $R_M \sim 100$ mg/sq ft		

* All values are in mg/sq ft

** Values in parentheses are R_M

Note: (obs) = observed
(calc) = calculated

high pressure spray chamber. This is especially shown by the increase in the value of the constant, a, from 0 05 to 0.4 on prewetting the Nevada soil, and from 0.1 to 1.9 on prewetting the clay soil.

It seems apparent that the prewetting resulted in movement of the small particles to the surface and the particles, in combination with chemicals in the soil that could form hydrated crystals of one type or another, then became more strongly bonded to the surface. Such a process could cause an increase in the number and perhaps the size of the particles not removable from the surface as well as an increase in the strength of the bond itself.

The data also indicate that the prewetting had less effect on the decontamination of the larger particles; but since the size range of the particles was not reported and no other experimental data have been obtained on the dependence of R_m on particle size for these methods, the trend of these effects as a function of particle size cannot be determined. These data also show that, for the smaller particles, wetting of contaminated surfaces prior to decontamination may result in particle-surface interactions other than only that due to gravity forces.

The initial soil mass loadings may be associated with the mass loadings expected in the depositions of fallout by means of $M_r(1)$. Thus, from Table 6.8 giving the $M_{\dot{r}}(1)$ values for a 1-MT surface land detonation, the calculated fallout mass loadings vary from values in excess of 300,000 mg/sq ft for 9800 r/hr at 1 hour about 4 miles from ground zero to about 1.3 mg/sq ft for 1 r/hr at 1 hour about 250 miles downwind. The data of Table 8.2 covers most of this range and, except for the lack of particle size data, would be applicable in estimating the maximum reduction in the air ionization rate that could be attained at all locations if contaminated smooth surfaces were decontaminated by application of either ... ese two methods.

8.3 Fallout from Detonations on Seawater

8.3.1 The Nature of Seawater Fallout

Most of the discussion in the previous chapters is concerned with fallout from land detonations. In this section, the nature of seawater fallout and its formation are discussed in some detail so that its contamination and decontamination properties can be described.

Seawater fallout consists of seawater and its salts, the radioactive fission product elements and induced activities, the components from the structural materials of the warhead or bomb, and, possibly, the structural materials of a target ship or submarine.

The simplest chemical system produced in a detonation on seawater occurs when no target is involved and when the weapon yield is large compared with the mass of the warhead. In this case, the elements from the warhead in the fallout may be as dilute as they are in the original seawater. The constituents of interest in the fallout, then, consist of only two components--the seawater and the radioactive elements. When this mixture is vaporized in the fireball, most of the fallout particles form by direct vapor condensation.

The first materials to condense are some of the less volatile fission product oxides, hydroxides, and/or chlorides along with vaporized sodium chloride from the seawater. As soon as the temperature decreases to about 100°C, the water vapor condenses on the small vapor-condensed sodium chloride particles that contain, by this temperature, most of the fission product elements. As the water condenses it may dissolve the sodium chloride and the fission products as ions. Some of these ions hydrate to form colloidal particles. The small drops coalesce to form larger drops or coalesce with inactive water drops entering the cloud at later times. At high altitudes, the drops freeze and do not remelt until they fall back to warmer altitudes.

The described process is similar to that for the land surface detonation except that (1) most of the condensation of the fission products is into or on vapor-condensed sodium chloride which is a water soluble substance; (2) these sodium chloride particles are expected to be very small; (3) the bulk substance, namely the water, cannot condense until most all of the fission products have condensed and, because of the low temperature for the water condensation, the time of formation for a given drop is relatively long; and (4) many of the fission products reach the earth in a liquid phase or in a soluble crystal phase.

When materials of the warhead or target are included in the fallout in large amounts, the presence of substances such as aluminum and iron complicates the condensation process. When present in large enough quantity, these substances form liquid vapor-condensed particles of their oxides (or hydroxides) which could serve as condensation sites for the gaseous species of the more refractory fission products. These materials solidify at higher temperatures than those at which the sodium chloride can exist as a liquid. The small particles and their agglomerates formed from the vapor condensation of the warhead or target materials can also serve as condensation sites for the sodium chloride, other less refractory fission products, and the water.

As the concentration or vapor pressure of the structural elements is decreased (by a decrease in the warhead-mass to yield ratio, for example), the onset of their initial condensation occurs at lower and lower temperatures and at longer times after detonation. At temperatures where the hydroxides become stable, they form, instead of the more vitreous oxides. At about the initial vapor

concentrations of the bomb materials where the vitreous oxide particles are not formed, the fallout chemical system begins changing to the simpler one described above.

Any technical treatment for discussion of the simpler chemical system must still include the interaction between the fission products and hydrous oxides. When the small fused oxide particles are formed, the fission product elements dissolved in the oxide matrix are neither ionic nor readily soluble. These small particles found in the fallout from some of the barge shots at the Eniwetok Proving Ground, as described by Adams, Farlow, and Schell[7], were not dissolved in water, and the radioelements inside them did not leach out in water.

Neither theoretical treatment nor data analysis are presently available for estimating which elements, and what fraction of each are, or could be, entrained in small fused magnatite or alumina particles. Therefore the description of the interactions of the various fission product elements, in the following sections, is limited to consideration of the presence of the warhead or bomb structural materials in such amounts that the hydroxides or the oxide-hydrates are the final vapor-condensed compounds formed.

Without a more complete treatment of the condensation (i.e. fallout formation) process, detonation conditions, such as the ratio of bomb mass to yield, cannot be defined for specifying the range or limit of initial vapor concentrations at which the hydroxides could exist. On the other hand an exact definition is likely not to be required as far as the effectiveness of many decontamination methods is concerned. Both the small particles and the insoluble hydroxides are difficult to remove; if anything, the hydrated oxides would probably be more difficult to remove by most methods, including high pressure spraying, than the small vitreous oxide particles.

The significant characteristics of seawater fallout with respect to its contamination of surfaces and its decontamination from surfaces are: (1) the carrier matrix is either a salt solution or a hygroscopic salt that is water soluble; (2) many of the radioelements in such a matrix are in ionic form; and (3) because the radioelements are ionic, or of colloidal size, they can move about in the matrix and can interact, on an individual basis, with the surfaces on which the salt particles or liquid drops land. Therefore, in describing the behavior and properties of the seawater fallout, consideration must be given to the interactions of each of the fission product elements in contamination and decontamination processes. The original treatment of the reactions expected from a seawater fallout and its decontamination, reported in Reference 4, was based on work by Miller, Cole, and Heiman[8]. The significant aspects of that treatment, with a few changes, are repeated in the following paragraphs.

8.3.2. Interactions of A Simple Ionic-Type Seawater Fallout

The simple ionic type fallout has extremely low concentrations of the warhead or bomb materials; it consists essentially of only seawater and fission products. In liquid drops of this mixture, each fission product is very dilute; hence, no interactions of importance occur within the drop once it is formed. In the following discussion, the radioelements are assumed to be present in their stable states in the seawater solution (pH7) either as ions or as colloidal particles. The first case considered, in describing the interactions of the ionic-type seawater fallout, is for a single drop of the fallout (as a water solution) landing on an impervious surface.

Let V_o be the original volume of the drop, A_o the area it covers on the surface, and i the number of moles of a given element contained in the drop. When the drop lands on a nonporous surface, the ions, or colloidal particles, of each element present in the solution immediately begin to be adsorbed by the surface. Under equilibrium conditions, the amount ultimately adsorbed depends on (1) the charge of the ions (or colloid), (2) their size, (3) their concentration, and (4) the nature of the surface. For environmental conditions in which the water evaporates, the salt concentration gradually increases and, if sufficient salt is present, visible amounts of salt crystals precipitate out as soon as both the surface and the liquid become saturated. When this stage of evaporation is reached, further adsorption by the surface ceases or becomes very slow, and, as the last few molecules of free water vaporize, the remaining unadsorbed ions or colloidal particles deposit in the salt crystals that cover the surface.

For this process, let

i_1 = the number of moles of the radioactive element adsorbed by the surface at any time after contamination

i_2 = the number of moles of the radioactive element in liquid phase (up to the time of crystallization).

For equilibrium adsorption up to and at the time of surface saturation, let

$$i_1 = a_1 C^n \tag{8.8}$$

in which a_1 and n are constants and C is the concentration of the element in the drop. Eq. 8.8 is an adaptation of the Freundlich adsorption isotherm.

When an ionic solution comes in contact with the surface, the initial adsorption rate of the ions by the surface is quite rapid; however, as soon as the liquid layers just above the surface become depleted in ions, the rate slows down to one that is controlled by the rate of diffusion of the ions (or colloids). In the evaporating drop, the concentration increases around the periphery of the drop; in most cases, the resulting concentration gradient produces a forced diffusion. This process occurs until the solution becomes saturated with salt.

If the rate of evaporation is very rapid, many of the ions are not able to reach the surface, and a large fraction of them are trapped in the crystal layer above the surface. In such a case, the ion concentration increases very rapidly at the vapor-liquid interface--with the interface moving at about the same speed as the diffusing ions---so that saturation and crystallization occur at this interface instead of adsorption at the surface-liquid interface. A warm surface, therefore, adsorbs less of an element from the solution than a cool surface. Thus temperature during the adsorption period is an important factor in determining how much of each element can be removed from the surface in a decontamination procedure that is applied at a later time.

Forced diffusion is likely to be in progress at the time when evaporation to dryness occurs. Therefore it was assumed that forced diffusion occurs over the whole evaporation period; under this assumption, the over-all concentration change in the drop may be written as

$$dC/dt = 0 \tag{8.9}$$

in which $C = i_2/V$ is the concentration of the radioactive element in the liquid and V is the volume of the drop at time, t. According to Eq.8.9, the ionic or colloidal material is being adsorbed by the surface at the same rate that evaporation decreases the volume of the drop. In other words,it gives the maximum rate for equilibrium adsorption. At constant temperature, the rate of evaporation of a drop larger than about 100 μ in diameter is essentially constant up to the time of saturation; the volume is then given by

$$V = V_o(1-gt), \quad 0 < t < t_d \tag{8.10}$$

in which V_o is the initial liquid volume of the drop, t_d is the final drying time, and $g = 1/t_d$ Combining Eqs. 8.9 and 8.10, and substituting i_2 for CV, gives

$$-di_2/i_2 = \frac{g\,dt}{1-gt} \tag{8.11}$$

Integrating, under the condition that $i_2 = i$ at $t = 0$, gives

$$i_2 = i\,(1 - gt) \tag{8.12}$$

At the time of saturation, t_s less than t_d; the quantity $(1-gt_s)$ is a positive constant, say k_2; at this time the volume of the drop is $V_o k_2$ so that the concentration, C, by aid of Eq. 8.12 is i/V_o. It may be noted that, with almost any adsorption process other than that described by Eq. 8.9 but subject to the above limits of integration, evaluation of the integral adsorption at $t_s < t_d$, would give the result that i_2 is proportional to i at t_s. Then, since the total salt in the seawater deposit (ca 0.5 molar) is constant for all values of i for all fission product elements, it follows that t_s is constant for each fission product and independent of i. Hence, Eq. 8.8 can be written as

$$i_1 = (a_1 / V_o^n) i^n \tag{8.13}$$

If the element is chemisorbed by the surface so that little or no desorption occurs during decontamination, or if the desorption rate is very slow, only that fraction of the radioactive element that is in the crystal layer on the surface is removed by a simple water wash.

The amount of the element remaining after decontamination, r, for no desorption, is equal to the amount adsorbed by the surface, i_1, and is given by

$$r = ai^n \tag{8.14}$$

in which $a = a_1/V_o^n$. Then the fraction remaining, or the decontamination ratio, for the drop ($F = r/i$), is

$$F = ai^{n-1} \tag{8.15}$$

The data for verification of Eq. 8.15 are shown in Figure 8.1 as taken from Reference 4. The cited data were obtained from experiments in which very large drops (300 μl) of solution, rather than small drops, were used. Adsorption curves as a function of time[8] showed that, for most of the elements, the amount adsorbed rose rapidly to a modest percentage as soon as the drops were deposited, and then it increased gradually as evaporation progressed. However, when the salt concentration approached saturation, the amount adsorbed rose very rapidly until salt crystals began forming; at that time the adsorption appeared to stop. These data were used as the basis of selecting t_s as the time for evaluation of the diffusion equation.

The important conclusion from the mathematical, or theoretical, treatment and data is that, as far as water washing is concerned, the adsorption process is irreversible and the amount of an element that is readily removable is limited to the fraction found in the surface layer of the water soluble salt crystals. Also, the fraction of the element found in the crystal layer increases if the evaporation of the water is rapid enough to override the diffusion process. Thus, a larger fraction of an element would be easily removable if the drop landed on a warm surface under low humidity conditions than if it landed on a cool surface under high humidity conditions.

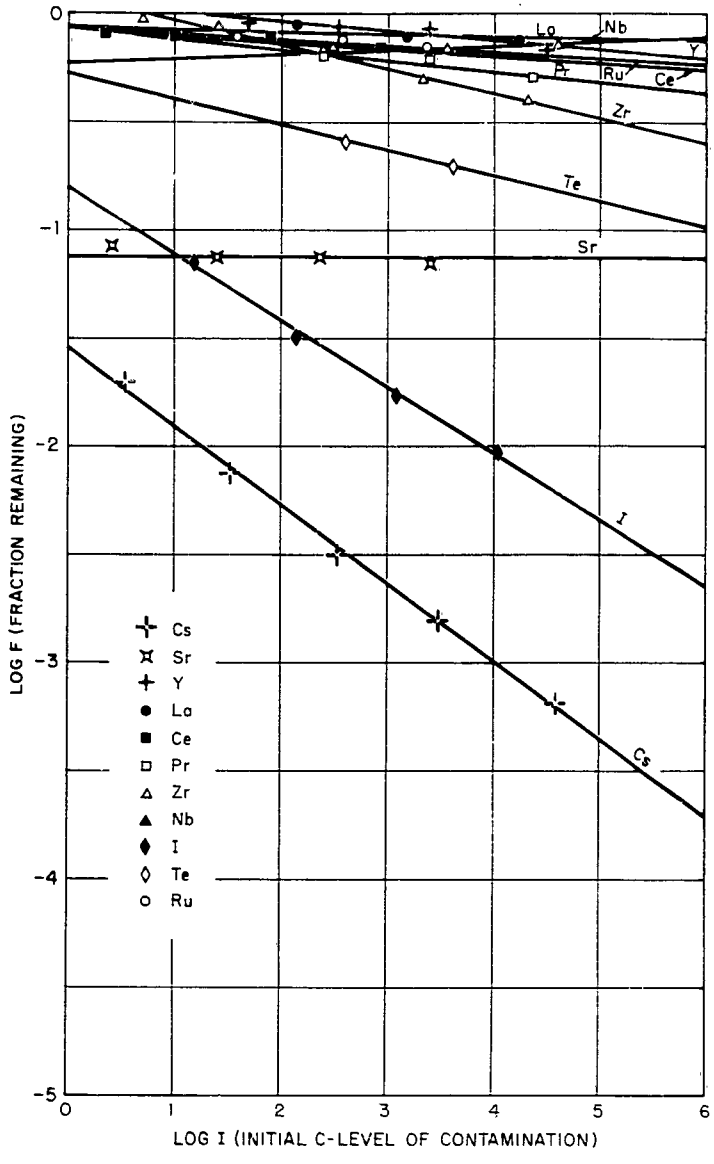
In case the drop evaporates to complete dryness during its fall through the atmosphere and lands as a dry salt crystal or as a crystal agglomerate, the amount of the element not removed by decontamination with water would be a very small fraction immediately adsorbed as the crystals dissolve in the wash water and the small amounts left behind due to incomplete rinsing of the surface. On the other hand, if the dried salt crystals remained on the surface for several weeks, the hygroscopic seawater salts would adsorb water from the atmosphere at night or when cool and become wetted. Within several days time the ions and colloids in the wetted salt would move to the surface through the water film around the crystals. The end result then would, not be much different from the case of the evaporation of the original water drop; that is, the ions and colloidal particles would be adsorbed by the surface from a saturated salt solution.

8.3.3 Interactions of a Seawater Fallout Containing Both Ionic and Hydrous-Solid Components

As previously discussed, fallout of this type may result from detonations in deep seawater in which the ratio of the warhead or bomb mass to yield is such that, in the fallout formation process, the hydroxides of elements like Al and Fe are the stable forms of their condensed states when condensation occurs. These hydroxides might also be present if a target ship is involved in the detonation. The presence of the hydroxides in sufficient concentration introduces a "solid" phase (i.e., an insoluble precipitate) in the condensed fallout drop.

The hydroxides, or hydrated oxides, of elements such as Al and Fe are good scavenging agentsfor many of the fission product elements; in other words, these radioelements have chemical interactions with the hydrous solids. The interactions of various fission product elements with the hydrated solids and the distribution of each element between the liquid phase and solid phase of a liquid drop of fallout are considered here in terms of simple thermodynamic equilibria.

Figure 8.1
VARIATION OF THE FRACTION REMAINING WITH INITIAL LEVEL OF CONTAMINATION OF 11 FISSION-PRODUCT ELEMENTS. THE SURFACE WAS CLEAN NAVY GRAY PAINT. THE DECONTAMINATION METHOD WAS IMMERSION STIRRING IN WATER.



Assuming that equilibrium conditions are attained in a drop of fallout before it lands on a surface, the concentration of an element in each phase may be estimated by equating the free energy of the element in each phase. For this equilibrium process, let

V_o = the initial volume of the drop

i = the number of moles of radioactive element in the drop

i_2 = the number of moles of the element in the liquid phase

i_3 = the number of moles of the element in hydrous solid phase

bi = the mass of the solids present in the drop and b is the ratio of the mass of the solid material to the number of moles of the radioactive element in the drop

S = the mass of the dissolved solids in the liquid phase of the drop

d = the density of the solid material

In Section 8.5, a relationship between the parameter b and the actual mass of the warhead is given. The solubility of the hydrated oxides considered (Al and Fe) is low; therefore S is taken to be zero in the following discussion. The volume of the solid phase in the drop is

$$V_3 = bi/d \tag{8.16}$$

and the volume of the liquid phase is

$$V_2 = (dV_o - bi)/d \tag{8.17}$$

With these volumes, the free energy relationship for the concentrations of an element in the two phases is

$$G_2^\circ + RT\ell n \frac{i_2 d}{(dV_o - bi)} = G_3^\circ + RT\ell n \frac{i_3 d}{bi} \tag{8.18}$$

in which G_2° and G_3° are constants for the reference free energy states of an element in the liquid and solid phases, respectively; R is the molar Boltzman constant; and T is the temperature in °K.

For a given element, the molar concentrations are proportional to the mass concentration. At the dilutions of the radioactive elements in the sea-water solution of the drop, the activity coefficients are unity; hence, the concentration is equal to the thermodynamic activity of the ion in both phases. At constant temperature, the equilibrium constant, K_a, for the reaction is given by

$$K_a = \frac{i_2\, bi}{(dV_o - bi)i_3} \tag{8.19}$$

The material balance constraint for the number of moles of an element in the drop is

$$i = i_2 + i_3 \tag{8.20}$$

Substitution of Eq. 8.20 in Eq. 8.19 gives

$$i_2 = \frac{i}{1 + \dfrac{bi}{K_a(dV_o - bi)}} \tag{8.21}$$

and

$$i_3 = \frac{i}{1 + K_a(dV_o - bi)/bi} \tag{8.22}$$

Equations 8.21 and 8.22 give the equilibrium distribution of a radioactive element in the liquid and solid phases, respectively. If Eq. 8.18 holds throughout the process of evaporation of all the water in the drop, from the time of formation of the original drop up to the time of crystallization of the soluble salts, then i_2, at the time of saturation, is the amount of the element in the water soluble salt crystals.

After the drop lands on a horizontal surface while it is still in the liquid form, the solids in the drop settle rapidly to the surface in the central portion of the surface covered by the drop. The ionic and colloidal elements in the drop are adsorbed on the surface covered by the drop as long as water is present. In the following discussion, it is assumed that the whole area covered by the drop is available for the adsorption process.

If Eqs. 8.8 to 8.11 are again used to compute i_1, and if Eq. 8.21 is used for the estimate of i_2 at $t = 0$ (V_o is the volume of the drop when it lands), then, at time of saturation, the amount of the element in the soluble crystalline deposit is given by

$$i_2 = \frac{i\,(1 - gt_s)}{1 + \dfrac{bi}{K_a\,(dV_o - bi)}} \tag{8.23}$$

The amount of the element chemisorbed on the surface is then

$$i_1 = a\left[\frac{i}{1 + \dfrac{bi}{K_a\,(dV_o - bi)}}\right] \tag{8.24}$$

It is seen that i_1 reduces to ai^n if b is very small and/or if K_a is very large (i.e., only a very small fraction of the element is in the solid phase); when the reverse is true, i_1 approaches zero. The amount of the element in the solid phase, noting that $i_1 + i_2 + i_3$ is equal to i, is

$$i_3 = \frac{bi\,(i - i_1)}{K_a\,(dV_o - bi_1) + bi} \tag{8.25}$$

where i_1 is given by Eq. 8.24.

Upon drying, the hydrous solids become firmly attached to the surface by physical adsorption. Dissolution of the solids, by acids or by physical removal methods, should result also in removal of the amount of the element, i_3, entrained in the precipitate.

Next, consider the process in which, after the deposit on the surface has "dried" or come to equilibrium, a volume, V, of water or other decontaminating solution is applied to the area covered by the drop. If some of the precipitate is dissolved into the solution, a proportionate amount of the radioactive element, previously entrained in the solid phase, is also dissolved and thus removed from the surface.

Additional amounts of the radioactive element may also transfer from the solid phase to the liquid phase; the amount that moves depends on the free energy of the element in each of the two phases. The amount of the element previously trapped in the soluble crystal phase, i_2, is dissolved into the decontaminating solution. For this system at equilibrium, the volume of the solid phase is

$$V_3 = (bi - K_s V)/d \tag{8.26}$$

in which K_s is the solubility of the solids per unit volume of decontaminating solution.

The free energy equation for the new distribution between the phases is

$$G_2^\circ + RT\ell n \frac{j_2}{V} = G_3^\circ + RT\ell n \frac{r_3 d}{(bi - K_s V)} \tag{8.27}$$

in which j_2 is the amount of the radioactive element in the liquid phase, and r_3 is the amount left in the solid phase when the liquid is removed. The equilibrium constant for this reaction is

$$K_c = \frac{j_2}{V} \frac{(bi - K_s V)}{dr_3} \tag{8.28}$$

The material balance for the radioelement is now

$$I = r_1 + r_3 + j_2 \tag{8.29}$$

Eliminating j_2 by use of Eqs. 8.28 and 8.29 gives

$$r_3 = \frac{(i - r_1)(bi - K_s V)}{dK_c V - K_s V + bi} \tag{8.30}$$

Assuming that no adsorption contamination of the surface occurs during the washing process, the total amount of the radioelement remaining on the surface covered by the drop is the sum, $r_1 + r_3$, or

$$r = \frac{dK_c V r_1 + i(bi - K_s V)}{dK_c V - K_s V + bi} \tag{8.31}$$

Using the previous finding that r_1 is equal, or proportional, to i_1, Eq. 8.24 may be substituted for r_1. Since $K_s V$ is negligibly small for the insoluble hydroxides of elements like Al and Fe in water, Eq. 8.31 can be written as

$$r = \frac{adK_c V/b}{(dK_c V/b + i)} \left[\frac{i}{1 + \frac{i}{K_a(dV_o/b - i)}} \right]^n + \frac{i^2}{dK_c V/b + i} \tag{8.32}$$

The constants, K_a and K_c, are not assumed to be equal because the physical state of the precipitate may have changed in drying. If their values are small and if most of the element is in the precipitate or solid phase, then r is equal to the last term of Eq. 8.32.

Because of the difficulty of determining all the constants of Eq. 8.32 from experimental data, and because the experimental data available for evaluating the constants was obtained from experiments in which the concentrations of solid in the contaminating solutions varied over a large range, Eq. 8.32 was simplified to

$$r = ai^n + \frac{i^2}{K + i} \tag{8.33}$$

where K is equal to dK_cV/b. With this simplification, the three equation constants can be determined from the experimental decontamination data at the low and high values of i. Equation 8.33 is a linear combination of r for two limiting conditions; the first term is for a pure adsorption interaction, and the second term is for a pure solubility interaction.

If either Eq. 8.32 or 8.33 is divided by i to give the fraction remaining, it may be noted that the first term predominates at low values of i and, for $n < 1$, decreases as i increases. The second term predominates as i increases and approaches unity as i becomes large.

In considering more than one drop of the seawater fallout on a surface, it is convenient to replace i with C_oV_o and sum over the number of drops. The fraction remaining, for Eq. 8.32, is then

$$F = \frac{a_o C_o^{n-2} V_o^{n-1}}{(K/C_o + V_o)\left[1 + \frac{bC_o}{K_a(d - bC_o)}\right]^n} + \frac{V_o}{K/C_o + V_o} \tag{8.34}$$

where a_o is dK_cV/b. If the concentration of an element in all the drops is the same initially, Eq. 8.34 reduces to

$$F = \frac{K_3 V_o^{n-1} + V_o}{K_4 + V_o} \tag{8.35}$$

in which K_4 is K/C_o and K_3 is $a_o C_o^{n-2}\left[1 + bC_o/K_a(d-bC_o)\right]^{-n}$. Since n is expected to be less than unity, the variation of F with drop size, or volume, is

similar to its variation with i. For small drops, where $K_4 > V_o$, F decreases as $K_3 V_o^{n-1} / K_4$. On the other hand, F approaches unity if V_o becomes sufficiently large; however, this limit is not attainable in seawater fallout.

The surface density of drops can be considered with regard to either (1) a surface loading sufficiently high to produce a completely wet surface, or (2) a low surface loading, in which the drops on a surface are separated from each other. In the case of the heavier loading, Eqs. 8.32 or 8.34 should apply as if the surface were covered with one large drop; for this case, i and r are changed to I and R in units of moles/unit area.

For the lighter surface loadings, the initial level I is

$$I = C_o \sum_{i=1}^{i=N} m_i V_i \tag{8.36}$$

where C_o is the concentration of the radioelement in the drops, m_i is the number of drops of volume V_i per unit area, V_i is the initial volume of the drop, and N is the total number of initial drop volumes on the area. Further, if the drops are all nearly the same size at a given location, the initial level is simply

$$I = C_o m_o V_o \tag{8.37}$$

where $m_o V_o$ is the total initial liquid volume deposited per unit area.

From the form of Eq. 8.35, the amount remaining, assuming again that C_o is the same in all drops, is

$$R = \sum_{i=1}^{i=N} m_i \frac{(K_3 V_i^n + V_i^2)}{K_4 + V_i} \tag{8.38}$$

If all the drop sizes are the same, R is simply $m_o r$ but the fraction of the element remaining is the same as for a single drop. In other words, for this case

$$R = I \frac{r}{i} \tag{8.39}$$

and

$$F = r/i \tag{8.40}$$

where r and i are constants because $C_s V_d$ is constant. If the condition of equal drop-concentrations and drop-sizes is approximated, F is independent of the level of contamination of the surface at surface densities less than saturation. In order to evaluate Eq. 8.38 for the case of differing drop sizes, the number distribution of the drop sizes must be known. The relationship would be more complicated if variations in the drop-concentrations were also considered.

8.3.4 Evaluation of Decontamination Equation Constants from Available Data

The only available data for comparison with the equations derived for the postulated interactions of the radioelements in seawater fallout are those reviewed in Reference 4. In the reported experiments, a synthetic seawater fallout solution was prepared to simulate fallout compositions that were, at the time, considered to be representative of the fallout from detonation conditions similar to that of the Bikini Baker Shot. Since no collections, and hence no analyses, of the fallout from that detonation were carried out, various estimates of a synthetic mixture to represent the fallout material were required later to specify its composition and methods of preparation for use in decontamination research.

This formulation was done by first estimating the atom percent at 1 day of the fission product elements that contribute significant amounts to the gamma radiation[3]. The amounts of each element from the detonation of a 20-KT yield pure fission weapon were then computed, and the concentrations of each was established on assuming they were mixed, or dissolved, in 2×10^6 tons of seawater. The concentrations for this particular solution was called the 1 C-Level of contamination. The solution, for simulating the fallout mixture, prepared with inactive carriers for each of 11 fission product elements at several multiples of the unit C-Level.

Decontamination experiments were carried out by tagging one of the fission product elements at a time with a radioactive tracer. Test surfaces were then contaminated with a constant volume of solution (300 μl) to determine the contamination behavior of each of the 11 elements.

The atom percentage of each element and its seawater concentration at the 1 C-Level are given in Table 8.3. The atom percentage of different fission products at several times after fission, for slow neutron fission of U-235, are given in Table 8.4, as taken from the summary by Bolles and Ballou.[9] Only those elements comprising more than 1 percent of the total number of fission product atoms, with the exception of Kr and Xe, are listed. The one-day percentage values, with a few exceptions, are very near to those of Table 8.3. It can be seen that a precise representation of the fission product element compositions from 1 hour to 1 year in synthetic fallout preparations for use in obtaining decontamination data at different times after detonation would involve a tremendous experimental effort.

Table 8.3

CONCENTRATION OF FISSION-PRODUCT ELEMENTS AT THE 1 C-LEVEL[a] IN THE SYNTHETIC SEAWATER FALLOUT

Element	Atom Percent of Total Fission Products at 1 Day	Concentration (moles/liter $\times 10^{10}$)
Cs	9.2	5.2
Sr	8.2	4.6
Y	2.9	1.6
La	3.5	2.0
Ce	10.2	5.7
Pr	3.9	2.2
Zr	17.0	9.6
Nb	1.0	0.56
Te	5.2	2.9
I	3.2	1.8
Ru	7.6	4.3

a. Concentration equivalent for level of gamma radiation.

In addition to the 11 fission product elements, Fe and Al were added to the synthetic preparations; the amounts of each that were added were determined by assuming the 20-KT weapon contained $5x10^3$ moles of Fe and $4x10^4$ moles of Al in its structural parts. When these elements were added, as diluted by the $2x10^6$ tons of seawater, the synthetic seawater fallout mixture was called the total carrier. The hydrous oxides of the elements were obtained by dissolving salts of Fe and Al in slightly acidic salt water with the other fission product carriers and then neutralizing the solution after the radioactive tracer was added.

The values of the constants of Eqs. 8.8 and 8.3 for some of the reported data are given in Table 8.5. A comparison of the calculated and observed fractions remaining is given in Table 8.6; the data are plotted in Figure 8.2. In general, the values of K are the highest for the more soluble elements and lowest for the least soluble elements, excepting for iodine (unless an insoluble iodine was formed with impurities in some of the salts or perhaps with Zr).

The bomb component materials (Al and Fe) had some effect on the constants a and n. Shifts in the derived values of the constants to both greater and smaller values occurred when the total carrier was used as the contaminating solution. In most cases, the effect on the constant a was to reduce its apparent value. The data for all the elements show a decrease in F with I at the low levels and an increase with I at the higher initial levels when the solid phase is present. (At concentrations less than the 10-C-Level, solutions of the synthetic fallout contained no visible solid phase.)

Additional data are available showing the effects of (1) chemical additives, (2) the physical force of water sprays, (3) the time of contact, and (4) the type of surface on the decontamination behavior of several fission product elements. The data are reviewed in the following paragraphs.

The decontamination constants for both +2 type and a +3 type ion, and for a colloid-forming element, decontaminated by use of (1) water, (2) an emulsifying agent, and (3) a complexing agent, are shown in Table 8.7. The emulsifying agent was only slightly better than water for removing Y and Nb, and had no effect on the decontamination of Sr. The complexing agent improved the decontamination Sr and Y by a factor of 2 but had no effect on the decontamination of Nb. These data show the relative effectiveness of the emulsifier for removing colloidal particles and suspending them in solution; they also show the relative effectiveness of the complexing agent for removing specific elements (as adsorbed ions) that form stable complexes with the agent.

Figure 8.2
VARIATION OF THE FRACTION REMAINING WITH INITIAL LEVEL OF CONTAMINANT OF SOME FISSION PRODUCT ELEMENTS IN THE TOTAL CARRIER CONTAMINANT. THE SURFACE WAS NAVY GRAY PAINT; THE DECONTAMINATION METHOD WAS IMMERSION STIRRING IN WATER

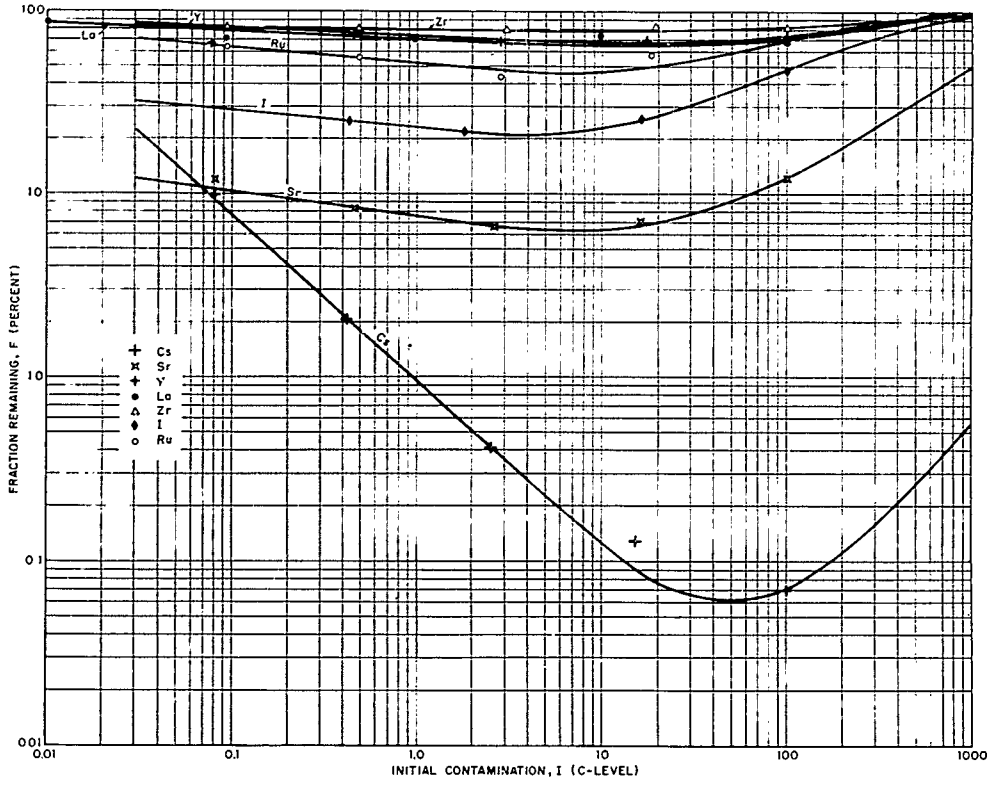


Table 8.4

PERCENT OF NUMBER OF ATOMS OF VARIOUS FISSION PRODUCT ELEMENTS AT DIFFERENT TIMES AFTER FISSION FOR SLOW NEUTRON FISSION OF U-235[a]

Element	1 hour	12 hours	1 day	1 week	2 weeks	1 month	3 months	1 year
Rb	1.0	1.8	1.8	1.9	1.9	1.9	1.9	1.9
Sr	9.6	7.8	7.1	6.5	6.3	6.0	5.1	4.5
Y	3.9	3.5	2.9	2.7	2.6	2.6	2.3	2.1
Zr	12.5	15.3	15.9	15.4	15.4	15.4	15.3	15.1
Mo	8.5	9.8	10.3	9.7	9.4	9.4	10.5	12.2
Ru	7.3	7.6	7.6	7.4	7.2	6.9	6.2	5.8
Te	6.0	3.1	3.0	1.7	1.4	1.3	1.2	1.2
I	6.8	4.8	3.6	1.3	0.91	0.58	0.51	0.53
Cs	4.2	3.9	4.9	7.6	8.5	9.0	9.1	9.0
Ba	7.2	6.1	6.1	5.2	4.6	3.8	3.2	3.2
La	5.5	3.6	3.3	3.4	3.4	3.3	3.2	3.2
Ce	8.0	10.3	10.2	8.8	9.1	9.3	8.4	7.0
Pr	1.3	1.2	1.2	2.5	2.3	2.1	2.7	3.0
Nd	4.7	6.5	7.0	7.3	7.7	8.2	9.0	10.0
Pm	0.55	0.84	0.74	0.56	0.85	1.2	1.4	1.2

a. From Reference 9

Table 8.5

DECONTAMINATION CONSTANTS FOR SOME FISSION PRODUCT ELEMENTS IN SYNTHETIC SEAWATER FALLOUT

Element	Seawater Carrier[a]		Total Carrier[b]		
	a	n	a	n	K
Cs	0.029 ± 0.003	0.637 ± 0.012	0.0096	0.106	176,000
Sr	0.075 ± 0.004	1.00	0.075	0.869	1,120
Y	1.155 ± 0.224	0.955 ± 0.024	0.73	0.951	570
La	0.857 ± 0.041	0.992 ± 0.009	0.70	0.950	620
Ce	0.880 ± 0.012	0.970 ± 0.004	-	-	-
Pr	0.870 ± 0.122	0.949 ± 0.019	-	-	-
Zr	1.218 ± 0.063	0.886 ± 0.008	0.79	0.981	1,010
Nb	0.593 ± 0.006	1.020 ± 0.001	-	-	-
Ru	0.898 ± 0.074	0.969 ± 0.014	0.53	0.915	200
Te	0.528	0.882	-	-	-
I	0.156 ± 0.012	0.694 ± 0.013	0.23	0.907	200
Np	0.106 ± 0.007[c]	0.912 ± 0.010	-	-	-

a. Data plotted in Figure 8.1; in C-Level Units

b. See Table 6.3 for carrier concentrations; data in C-Level Units

c. For i = fraction of the FP C-Level (FP = fission product)

Method: immersion stirring apparatus (5-minute immersion)
Reagent: 250 milliliters H_2O
Time of contact before decontamination: 21 hours at 30°C
Source of data: Reference 8
Surface: Navy gray paint
Combined effect of FP in the seawater carrier in correct relative concentrations:
a = 0.686 ± 0.007, n = 0.940 ± 0.001 (not accounting for Np)

Table 8.6

EFFECT OF INITIAL LEVEL OF CONTAMINATION ON THE DECONTAMINATION OF SOME FISSION PRODUCT ELEMENTS USING TOTAL CARRIER SYNTHETIC SEAWATER CONTAMINANT

i (C-Level)	F(observed) (percent)	F(calculated)[a] (percent)	i (C-Level)	F(observed) (percent)	F(calculated)[a] (percent)
Cs			Sr		
0.080	10.	9.3	0.080	12.	11.
0.42	2.1	2.1	0.46	8.4	8.4
2.5	0.42	0.42	2.6	6.7	6.7
15.	0.13	0.092	16.	7.2	6.7
100.	0.072	0.072	100.	12.3	12.3
Y			La		
0.076	67.	82.	0.010	88.	86.
0.45	76.	76.	0.091	71.	78.
2.8	69.	70.	0.96	70.	70.
17.	70.	67.	9.6	74.	65.
100.	74.	74.	100.	71.	71.
Zr			Ru		
0.092	82.	82.	0.092	64.	64.
0.48	80.	80.	0.48	56.	56.
3.0	79.	78.	2.8	44.	48.
19.	82.	78.	18.	58.	49.
100.	81.	82.	100.	69.	69.
I					
0.087	82.	29.			
0.43	25.	25.			
1.8	22.	22.			
16.	26.	25.			
100.	48.	48.			

a. Using Eq. 8.32 and constants given in Table 8.5
Method: immersion stirring apparatus (5-minute immersion)
Reagent: 250 milliters H_2O
Time of contact: 21 hours at 30°C
Source of data: Reference 8
Surface: Navy gray paint

The relative decontamination effectiveness of tripolyphosphate, in both the stirrer method and the high-pressure spray chamber, is given in Table 8.8 for several elements at 1 day and 14 days contact time (with the temperature maintained at 30°C). With this reagent, the removal of Sr was only about 1/3 as effective as water; this decrease in effectiveness with the tripolyphosphate was apparently due to the formation of small insoluble Sr phosphate particles during decontamination. The largest improvement in decontamination, with this reagent, was for Y and Ce (rare earths). In the stirrer method of decontamination, the reagent was more effective at the later time of decontamination; with the spray method, the general effectiveness of the reagent decreased somewhat at the later time.

The decontamination effectiveness of the stirrer method and the high pressure spray chamber are compared in Table 8.9. These data show relative effectiveness values as large as 85 for the high pressure spray at the one day contact time. However, with the soluble elements, Cs and I, the ratio was practically unity. At 14 days, relative effectiveness of the spray chamber was only as high as 7 or 8; the F values themselves indicate that about half or more of this reduction in relative effectiveness was due to the increased effectiveness of simple water washing procedure (stirrer method) and the remainder due to a decreased effectiveness of the spray chamber.

While the increased effectiveness of the stirrer method at the 14 day contact time might be attributed to a gradual deterioration of the paint surface in contact with the salts, it is not certain that the same deterioration would decrease the effectiveness of the high pressure spray. One possible explanation is that the corrosion causes an increase in the microporosity of the surface, and the spray itself forces some of the contaminating atoms or surface corrosion products into the depressions. As noted above, Sr did not decontaminate as well with tripolyphosphate as with water. In all the decontamination methods, iodine had an F value of about 25 percent at 1 day and about 62 percent at 14 days. This information, along with data on the decay of iodine remaining on the test samples and the radiographs of the deposits, proves that the iodine that was not washed from the plates had reacted chemically with the paint. This behavior is not accounted for by the decontamination equations; it could well be the real cause of the low K value noted in Table 8.5.

The dependence of the equation constants a, n, and K on the contact-time, for water washing and high pressure spraying, are given in Table 8.10. The functional dependence of the equation constants on the time of contact was obtained from data in which fresh mixed fission products were used as the radioactive tracer in the total carrier. No data are presently available for determining variation with contact-time of the decontamination equation constants for each fission product element separately.

Table 8.7

DECONTAMINATION CONSTANTS FOR SOME FISSION PRODUCT ELEMENTS IN A SYNTHETIC SEAWATER FALLOUT: EFFECT OF CHEMICAL ADDITIVE

Element	Reagent	Total Carrier		
		a	n	K
Sr	H_2O	0.075	0.822	8,100
	Emulside 680-B	0.075	0.822	8,100
	EDTA	0.042	0.822	19,000
Y	H_2O	0.71	0.958	3,900
	Emulside 680-B	0.51	1.052	∞
	EDTA	0.36	0.958	2,200
Nb	H_2O	0.62	1.020	4,700
	Emulside 680-B	0.53	1.00	1,600
	EDTA	0.62	1.020	4,700

Method: immersion stirring apparatus (5-minute immersion)
Reagents: 250 milliliters (0.8 percent solution of additives)
Time of contact: 21 hours at 30°C
Source of data: References 8, 10, 11
Surface: glossy sea blue lacquer

Table 8.8

RELATIVE EFFECTIVENESS OF TRIPOLYPHOSPHATE REAGENT WITH RESPECT TO WATER FOR THE DECONTAMINATION OF SEVERAL FISSION PRODUCT ELEMENTS FROM GLOSSY SEA BLUE LACQUER[a]

Element	$F(H_2O)/F(tripoly)$			
	Stirrer Method		Spray Chamber Method	
	1 day	14 days	1 day	14 days
Cs	1.6	2.6	1.4	0.43
Sr	0.35	0.38	0.35	0.35
Y	1.1	2.3	2.8	2.0
Ce(Pr)	1.2	2.8	2.1	1.3
Zr	0.95	1.9	1.0	1.2
Nb	1.0	1.2	0.64	0.88
Ru	1.1	1.1	3.9	1.7
I	1.2	0.98	1.0	1.1

a. Total Carrier Contaminated with Synthetic Seawater Fallout at the 100 C-Level Concentration.

Source of Data: Reference 10.

Approximate values of the decontamination equation constants for Navy gray paint, galvanized iron plate, concrete, and asphaltic concrete are given in Table 8.11. These data were obtained from a freshly mixed fission product tracer containing excess uranium and therefore the absolute values of the constants are not as reliable as those previously given. However, on a relative basis, they indicate similar decontamination behavior of both the asphalt and the paint surfaces. The galvanized iron surface, although not decontaminated to the degree of the paint or asphalt, also indicated decontamination behavior corresponding to the decontamination equations. The exception was the spray decontamination of concrete surfaces; in this case, the F values did not increase with deposit level at the high initial deposit levels. The hydrous precipitate did not appear to bond to the concrete surface very strongly, and F decreased more or less linearly with the initial deposit level at the higher levels.

Table 8.9

EFFECT OF TIME OF CONTACT, METHOD, AND REAGENT ON THE DECONTAMINATION OF SOME FISSION PRODUCT ELEMENTS USING TOTAL CARRIER SYNTHETIC SEAWATER FALLOUT AT THE 100 C-LEVEL CONCENTRATION

Element	1-day Contact			14-day Contact		
	F(Stirrer) (percent)	F(Spray) (percent)	$\frac{F(Stirrer)}{F(Spray)}$	F(Stirrer) (percent)	F(Spray) (percent)	$\frac{F(Stirrer)}{F(Spray)}$
1. Water						
Cs	0.16	0.13	1.2	0.23	0.03	7.7
Sr	22.	8.	2.8	8.3	12	0.69
Y	80.	2.4	33.	34.	8.6	4.0
Ce(Pr)	83.	3.8	22.	47.	6.0	7.8
Zr	82.	6.3	13.	33.	14.	2.4
Nb	81.	2.1	39.	36.	8.3	4.3
Ru	80.	3.5	23.	33.	7.8	4.2
I	24.	26.	0.92	62.	65.	0.95
Average	56.	6.5	-	32.	15.	-
2. Sodium Tripolyphosphate[a]						
Cs	0.10	0.09	1.1	0.09	0.07	1.3
Sr	62.	23.	27.	22.	34.	0.65
Y	70.	0.87	80.	15.	4.2	3.6
Ce(Pr)	67.	1.8	37.	17.	4.6	3.7
Zr	86.	6.1	14.	17.	12.	1.4
Nb	79.	3.3	24.	29.	9.4	3.1
Ru	76.	0.89	85.	30.	4.5	6.7
I	20.	26.	0.77	63.	59.	1.1
Average	58.	7.8	-	24.	16.	-

a. 0.8 percent solution of $Na_5P_3O_{10}$

Source of data: Reference 10

Surface: Glossy sea blue lacquer

Table 8.10

DEPENDENCE OF THE DECONTAMINATION PARAMETERS
a, n, AND K ON TIME OF CONTACT

Method	a	n	K
Immersion Stirrer	$1.00\ t^{-0.0511}$	$0.643 + 0.00056t$	$1150\ t^{-0.0553}$
Spray Chamber	$0.748\ t^{-0.0511}$	$0.302\ t^{0.367}$	$4630\ t^{-0.0553}$

t = time of contact in days.

Source of data: Reference 11.

Surface: Navy gray paint.

8.3.5 The Residual Number and Fraction of Ionization Rate Remaining After Decontamination

The data of the previous section show that, because of the different contamination and decontamination behavior of the various elements in seawater fallout, the fission product mixture is fractionated when surfaces are decontaminated with water or with water solutions of chemical reagents. This means that the ionization rate of the mixture of radionuclides remaining on the surface after decontamination will not decrease with time in the same way as it would for the radionuclide mixture on surfaces that are not decontaminated.

Further, if the variation with time of the ionization rate from the radioelements remaining on the decontaminated surface is significantly different from that of the original mixture, the exposure dose from the fractionated mixture cannot be estimated from a "normal" decay curve or knowledge of the decay curve of the original mixture. When this is the case, the effectiveness of the decontamination is not appropriately determined from a ratio of the ionization rates before and after decontamination (corrected to a common time) such as defined by $F_r(t)$.

The effectiveness of decontamination, as a countermeasure, is usually defined as the ratio of the exposure dose with use of the countermeasure to that without use of the countermeasure. The name given to this ratio is the Residual Number (RN);[12] its use is discussed in some detail in Chapters 11 and 12.

Table 8.11

APPROXIMATE DECONTAMINATION CONSTANTS FOR NAVY GRAY PAINT, GALVANIZED IRON, CONCRETE, AND ASPHALT AT SEVERAL TIMES OF CONTACT

Time (days)	Immersion Stirrer			Spray Chamber		
	a	n	K	a	n	K
1. Navy Gray Paint						
1	0.67	0.747	1730	0.20	0.334	25,000
7	0.65	0.764	980	0.42	0.387	16,000
14	0.84	0.787	1480	0.62	0.317	12,000
2. Galvanized Iron						
1	1.00	0.949	14,400	0.78	0.943	18,400
7	1.00	0.974	14,400	0.71	0.930	6,000
14	1.00	0.973	14,400	0.65	0.929	10,700
3. Concrete						
1	0.96	0.984	23,000	0.85 [a]	0.961 [a]	-
7	1.00	0.982	23,000	0.89 [a]	0.954 [a]	-
14	1.00	0.987	23,000	0.79 [a]	0.964 [a]	-
4. Asphalt						
1	0.78	0.839	2210	0.25	0.931	25,000
7	0.76	0.855	1730	0.32	0.922	30,000
14	0.78	0.931	2720	0.50	0.894	20,000

a. For i = 1 to 650 in C-Level Units;
For i = 650 to 3400, F(percent) = 78 - 0.019i.

Source of data: Reference 13.

For a contaminated surface area of a limited size, the residual number for decontaminating seawater fallout can be defined by

$$RN(t) = \frac{\int_{t_1}^{t_2} R(t)\,dt}{\int_{t_1}^{t_2} I(t)\,dt} \tag{8.41}$$

in which I (t) is the ionization rate from a contaminated surface from t_1 to t_2 and R (t) is the ionization rate from a decontaminated surface (whose ionization rate would be given by I (t) except for the applied decontamination procedure) and t is the time since detonation. When R (t) is directly proportional to I (t), RN is equal to F_∞; this proportionality is usually assumed for fallout from detonations on land areas.

In addition to the variables discussed in the previous section, the values of R (t), and hence RN (t), depend on the time after detonation when the decontamination is done and the time intervals over which an exposure to radiation occurs. The decontamination time is involved because the relative abundances of the elements in each mass chain change with time. For example, Ba decontaminates more readily than La, so that removal of the parent nuclide (s) Ba (or Cs) at an early time would result in an equivalent reduction in the radiations from the daughter product, La; the reduction in the radiation would be much less if the daughter product (s) was decontaminated at a later time.

Values of both $F_r(t)$ and RN (t), obtained from measurements of the decay of fission products remaining on an impervious surface after decontamination, were derived by W.B. Lane;[14] the data are shown in Figures 8.3 and 8.4. The fission product source activity used in the experiments was obtained from a short high-flux neutron activation of a quartz-encapsulated specimen of U-235 enriched uranium metal. The sample contained about 0.2 neutron captures by U-238 per fission. The activated specimen was dissolved in acid and then mixed with the total carrier synthetic seawater fallout solution; next, the solution was neutralized and then aspirated in a chamber in the form of a fine mist which settled over a period of time onto the surface of painted sample plates. The activity levels on the plates before and after decontamination were measured by use of a standard high-pressure ion chamber[15] so that the data are essentially proportional to air ionization rates.

The RN values of Figures 8.3 and 8.4 are for integrations of R (t) and I (t) from the time of the first reading after decontamination to a stated later time. Normally, the decay curve of the remaining radionuclides, or R (t), could be reconstructed from $F_r(t) \times I(t)$ where I (t) might be given by the normal fission-product ionization rate as given in Table 3.13, or, in this case, by the data in

Figure 8.3
VARIATION OF FRACTION OF IONIZATION RATE REMAINING AND CALCULATED RESIDUAL NUMBER FROM TIME OF DECONTAMINATION WITH TIME AFTER FISSION FOR SAMPLES OF NAVY GRAY PAINT SURFACES CONTAMINATED WITH FRESH FISSION PRODUCTS IN A SIMULATED SEAWATER FALLOUT
(a) Immersion stirrer method with water (25°C)
(b) Spray method with water (75°C)
(c) Spray method with water (25°C)
(d) Spray-brush method with water (25°C)

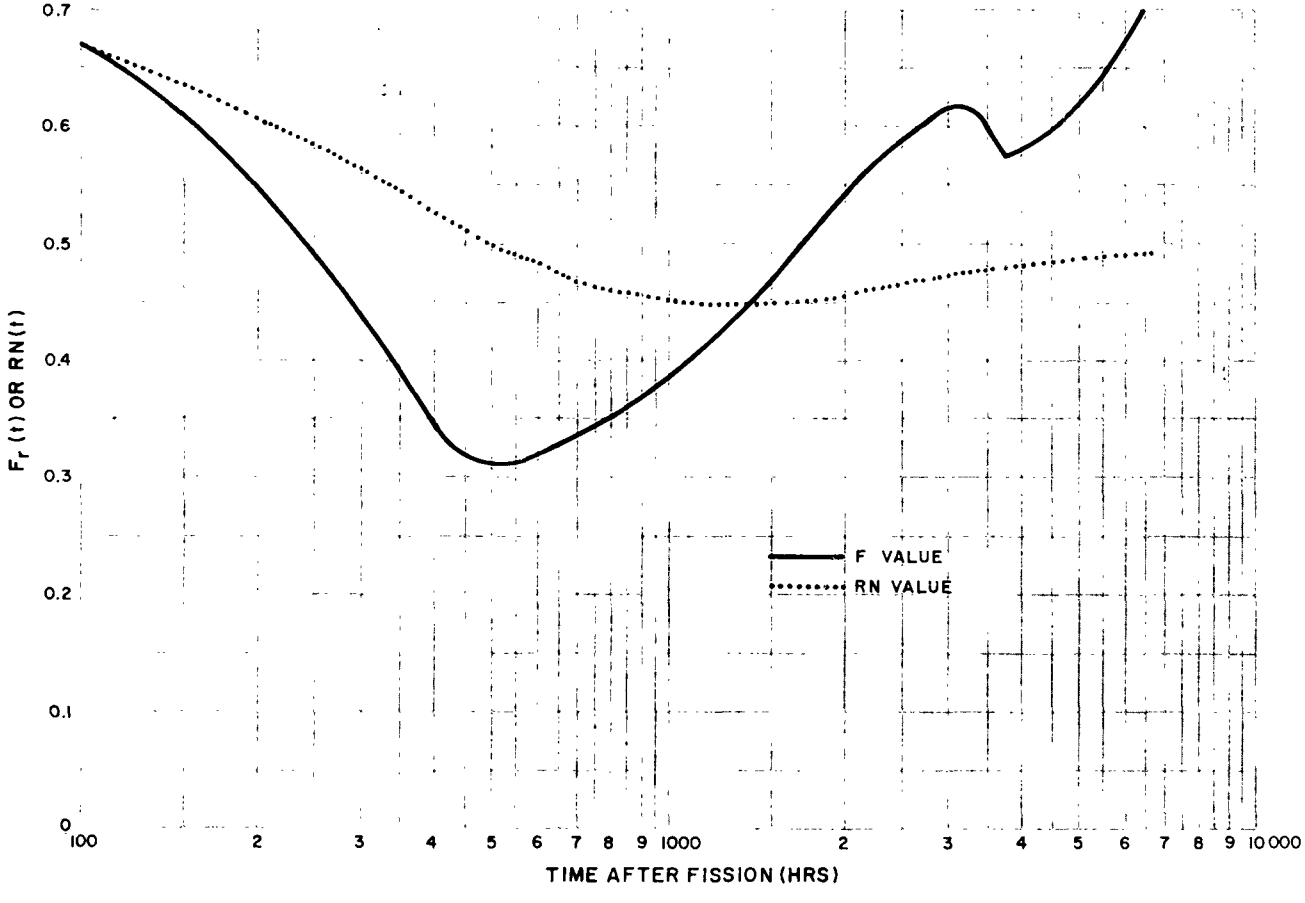


FIG. 8.3 (continued)

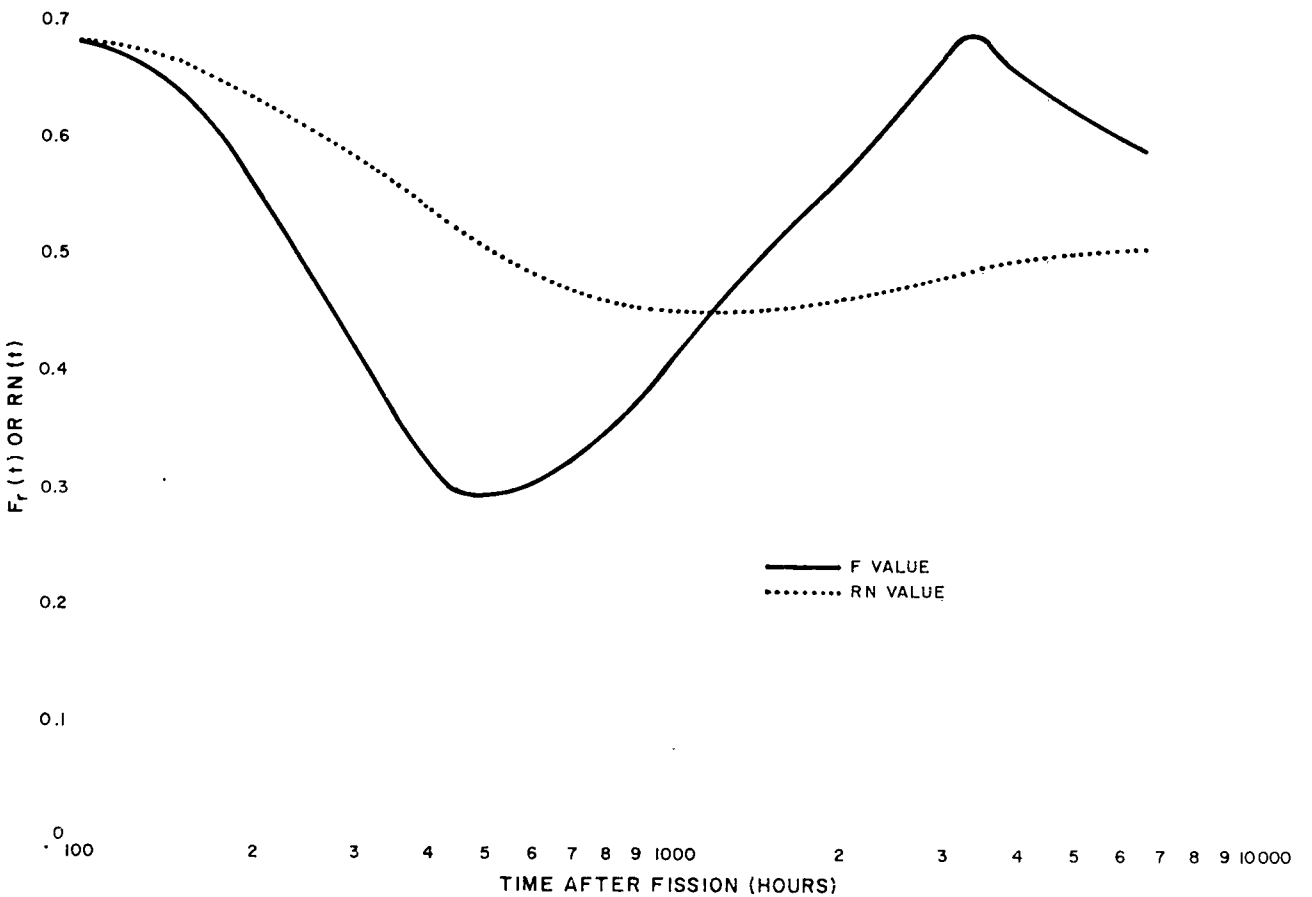


FIG. 8.3 (continued)

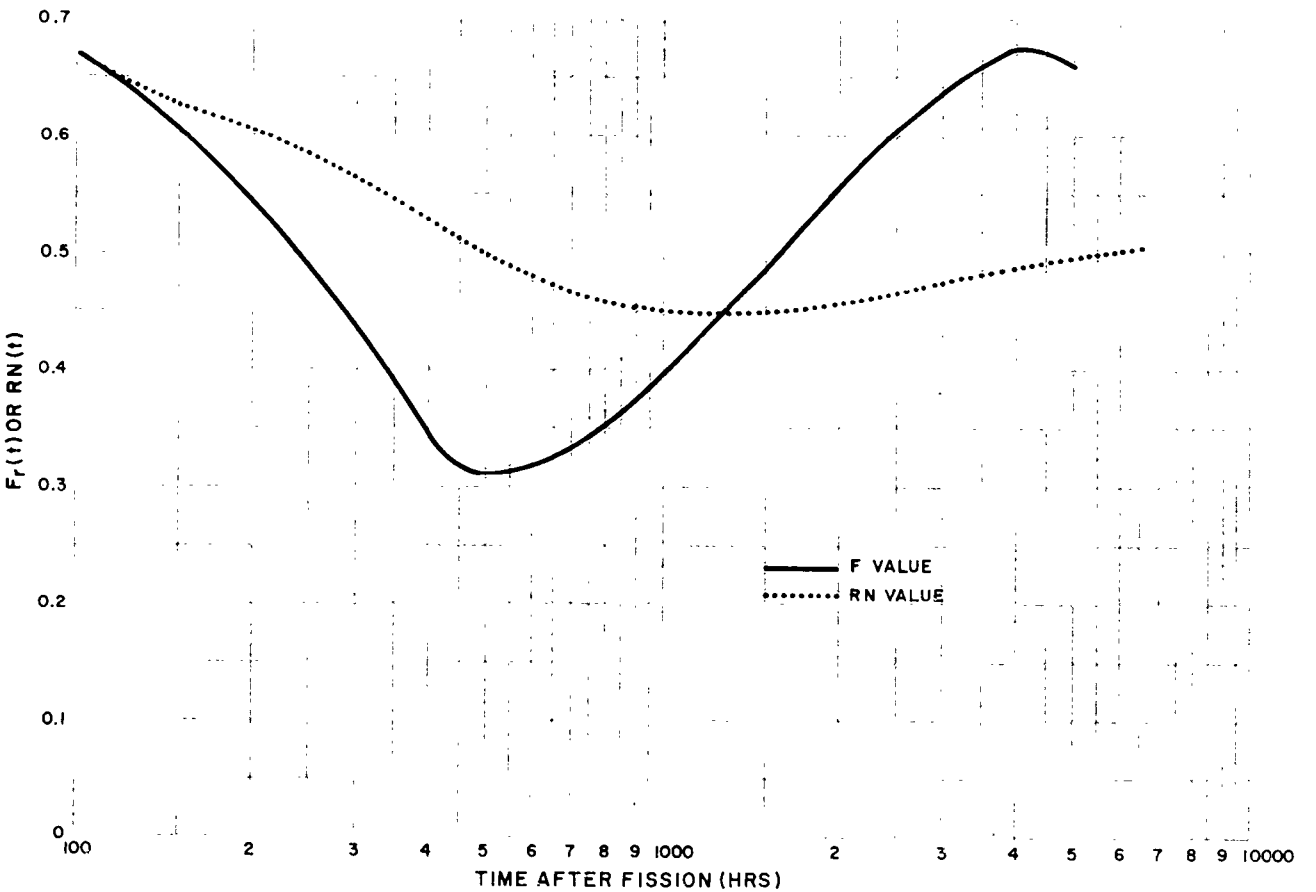


FIG. 8.3 (concluded)

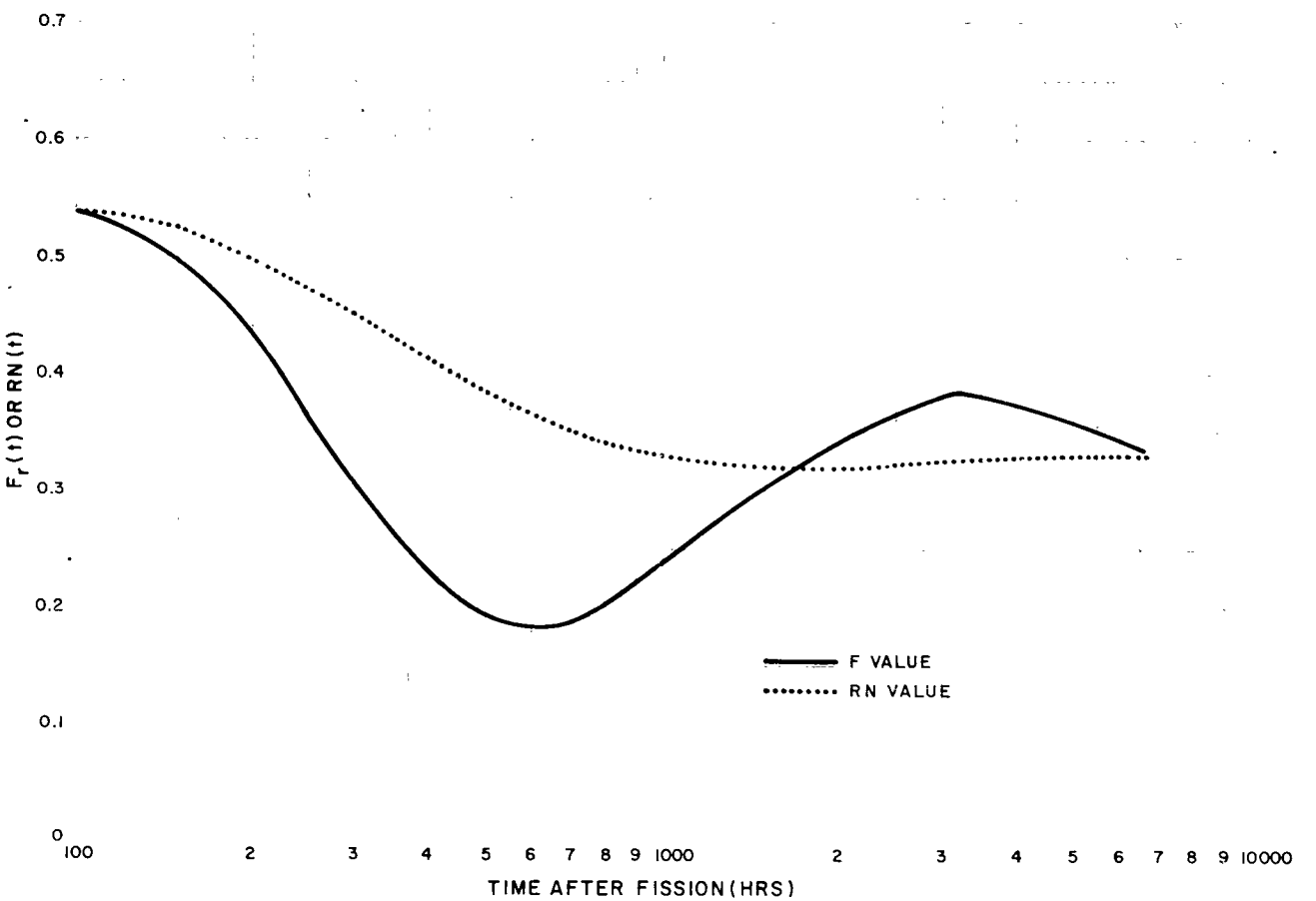


Figure 8.4
VARIATION OF FRACTION OF IONIZATION RATE REMAINING AND CALCULATED RESIDUAL NUMBER FROM TIME OF DECONTAMINATION WITH TIME AFTER FISSION FOR SAMPLES OF NAVY GRAY PAINT SURFACES CONTAMINATED WITH FRESH MIXED FISSION PRODUCTS IN A SIMULATED SEAWATER FALLOUT
(a) Immersion stirrer method with an 8% solution of EDTA (25°C)
(b) Immersion stirrer method with an 8% solution of Orvus (25°C)
(c) Spray-brush method with an 8% solution of Orvus (75°C)

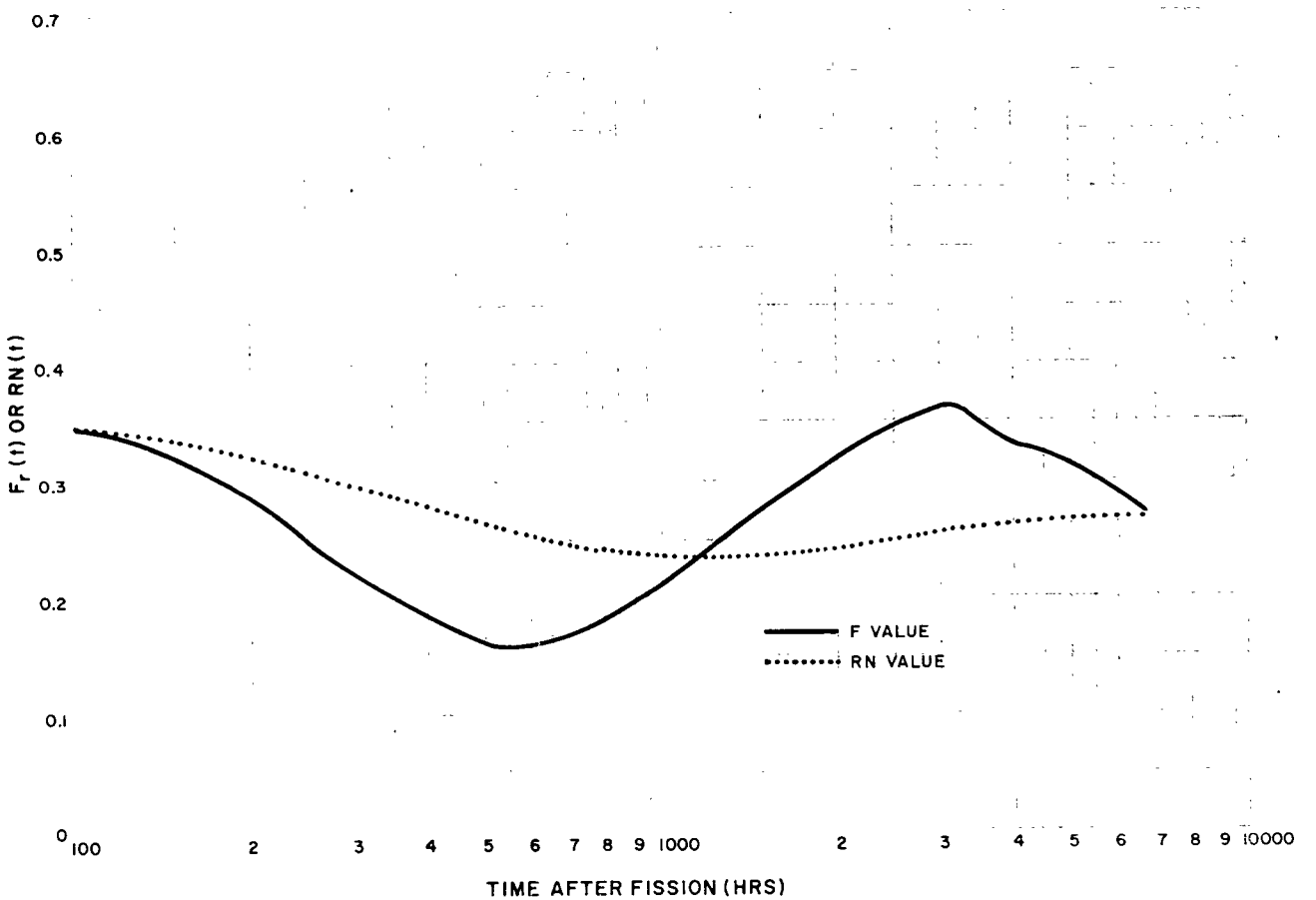


FIG. 8.4 (concluded)

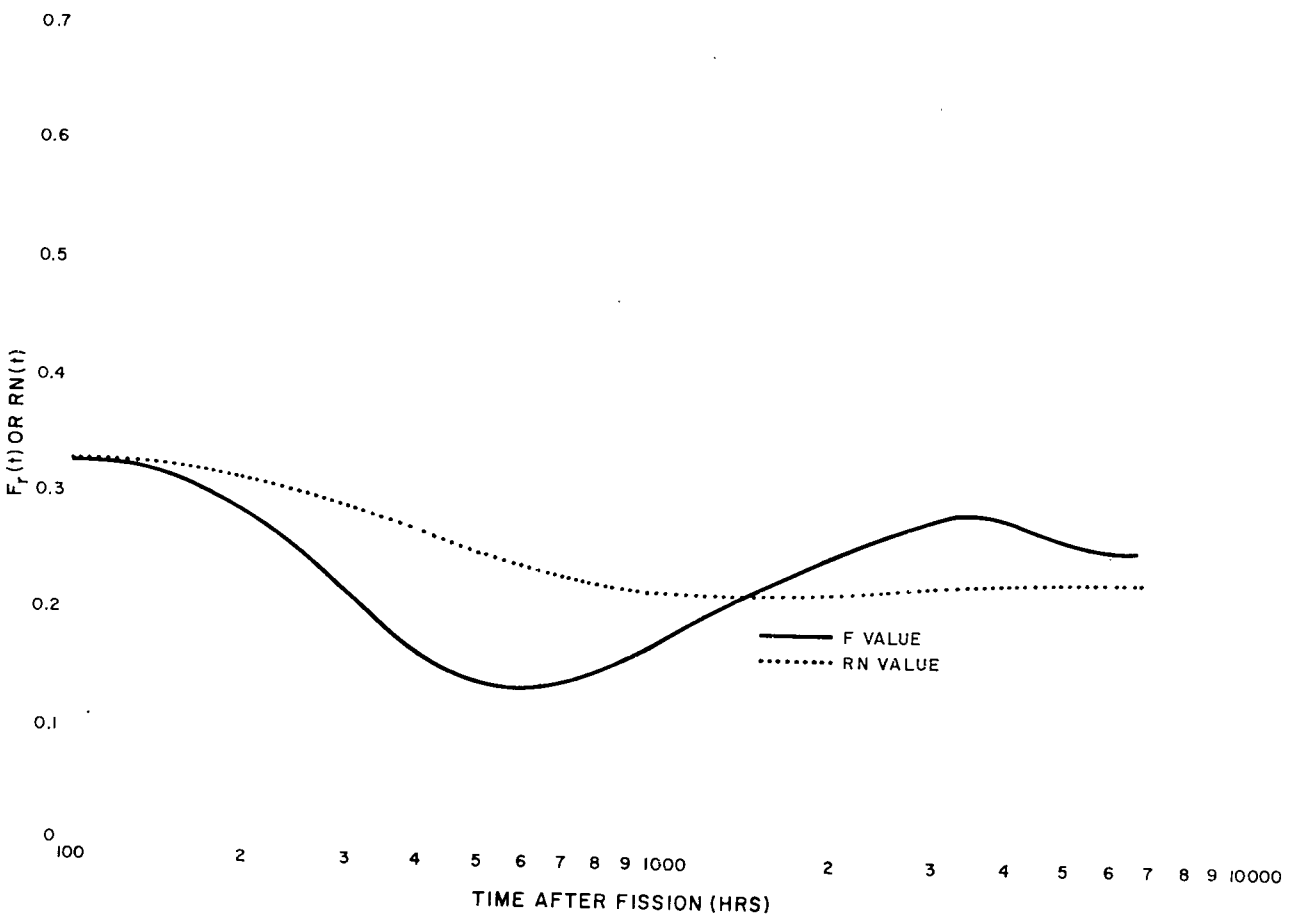
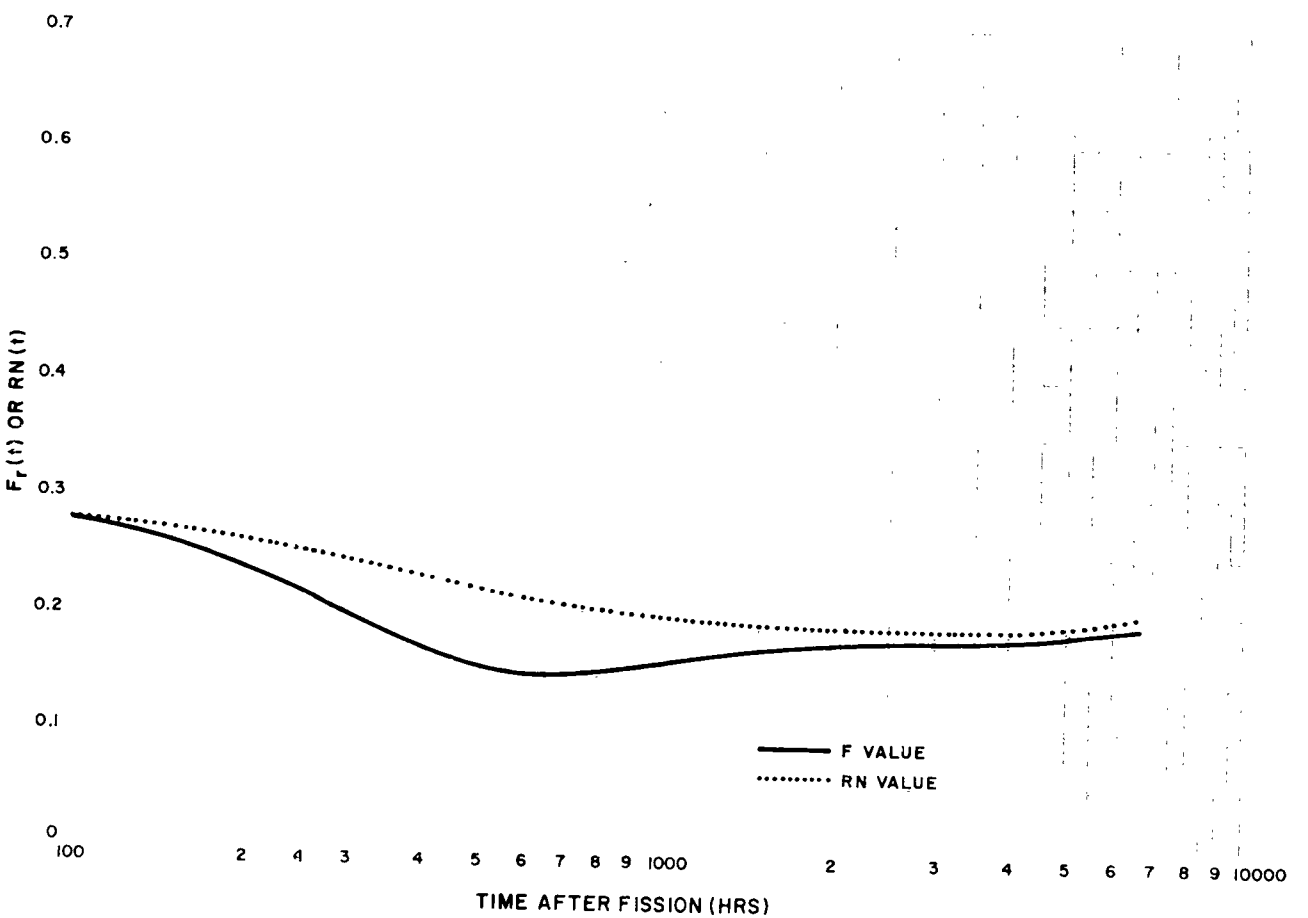


FIG. 8.4 (continued)



Reference 15. However, the apparent fission yield of the mass numbers 140 and 131 in the source activity was found to be low; the yield of mass number 140 was about 30 percent low (presumably due to losses of the Xe product into the quartz during bombardment), and most of the mass number 131 was lost, possibly during the processes of dissolution of the specimen. Some variation in the mass chain yields would be expected, because of the finite time of neutron bombardment, but the effect of the time of activation on the decay curve at 100 hours later should be negligible.

The contamination levels of the surfaces in these experiments reported by Lane are not directly comparable to any one of the C-Levels of contamination used in the experiments described in the previous section. The actual initial surface density of the fission products in Lane's experiment was not determined; however, the contamination level on all the samples was approximately the same. The fractionation of the radionuclides caused by the decontamination procedures, relative to the initial source activity, is shown best by $F_r(t)$. The minimum in $F_r(t)$ at about 500 hours is due to the depletion of the Ba(La)-140 nuclide pair. The maximum, at 3000 to 4000 hours, is due to the relatively less effective removal of the elements Zr and Nb, and possibly Ru, as well as of the rare earth elements Ce and Pr.

In these particular experiments, the decontamination by the stirrer and spray chamber method, using water, gave about the same results. Some improvement in the removal effectiveness is shown when the samples were brushed mechanically while being spray-cleaned. In Figure 8.4, the curves for the complexing agent, EDTA, show a marked improvement in effectiveness relative to decontamination using water; the cleaning agent, Orvus, was even more effective than EDTA. With the latter, the peak in $F_r(t)$ at 3000-4000 hours has disappeared. The reason for the poorer results for the spray-plus-brush decontamination using the Orvus cleaning agent is not known.

It is likely that the early part of all the $F_r(t)$ and RN (t) curves would be lower if the iodine (mass number 131) had been present. Its absence (or presence) would not, of course, affect the shape of the curves after about 1000 hours since, by that time, the iodine activity would have decayed to a very low level.

The values of the RN (t), calculated for exposure doses starting at the time of decontamination, tend to level off at a constant value after about 1000 hours. Thus, for long term exposures, the calculated RN (t) values give the effectiveness of the decontamination method. However, for relatively short exposure times the $F_r(t)$ curve should be used as a measure of the decontamination effectiveness rather than the RN (t) given in the figures. The data illustrate quite well the gross differences in R (t) relative to I (t) that could result in the decontamination of seawater fallout with water or water solutions containing

chemical additives. The shapes of the curves would be expected to be different for decontamination (or contact) times other than 100 hours after detonation.

Further studies of this type could perhaps provide data from which optimum combinations of decontamination times, methods, and reagents could be derived. The relative effectiveness of one method to that of another can be determined by taking the inverse ratio of their respective RN (t) values.

8.4 Fallout from Detonations In A Harbor

8.4.1 Definition of the Contaminated System

The discussion in Chapter 7, on the likely composition of the fallout from harbor detonations, presents rough estimating procedures for computing the relative amounts of harbor bottom mud and seawater. To describe the decontamination behavior of a set of mud and seawater (slurry) mixtures, the distribution of each radioelement among the liquid, hydrous solid, and mud phases must be specified. These distributions should depend not only on the relative amounts of mud and seawater that are involved in the explosion but also on the proximity of the explosion center to the harbor bottom mud. Detonations in very shallow water may produce fused particles from the bottom mud; in such case the hydrous solids would be eliminated and some of fission would condense into the fused particles. The same general result would occur if the warhead, or bomb, mass were large relative to the total yield.

For every harbor detonation fallout that initially contained an appreciable amount of seawater, a predominant fraction of the mud would not be fused. In a land surface detonation, with the fireball in contact with the soil, only a relatively small fraction of the crater soil is fused and an appreciable fraction of the fallout consists of unmelted particles. Therefore, when the soil, or the harbor bottom mud, becomes farther removed from the point of detonation, (by an intervening layer of water), its likelihood of entering the fireball soon enough to be melted would be reduced.

In the slurry mixtures, or harbor-detonation fallout, the chemical interactions in the slurry drop itself might determine the final distribution of a radioelement among the phases. For example, if a radioelement that condensed into fused particles (in the case they were formed) also adsorbed strongly on unfused soil mineral grains, then it would always decontaminate with the soil fraction. Further, this decontamination behavior would always predominate as long as any particles were present in the fallout drop.

On the other hand, many elements that condense very little into fused particles, would condense in the liquid (water) phase and then absorb onto the

unfused soil particles. Therefore, when these kinds of reactions occur, they would tend to control the distribution of many elements among the various phases in the slurry drop as well as in the contamination reactions with the surface on which the drop lands.

The contamination process, after a slurry drop lands on a surface, may be,first, the dense solid (mud or soil) particles fall rapidly to the surface; the less dense hydrous oxides settle slowly to the surface and over the solid particles. The water, over a period of time, evaporates and leaves a deposit of salt crystals. As long as water is present the whole area covered by the drop would be subject to contamination by the ionic species in the liquid phase of the drop. However, the fraction of the drop-area that is covered by the mud is probably best described by Eq. 8.2.

In decontamination, the amount of the element associated with the mud particles should be removed with the same effectiveness as the mud; this is given by

$$R_1 = C_s R_M (1 - e^{-k_f I_m}) \tag{8.42}$$

where R_1 is the amount of the element remaining, in moles/sq ft; C_s is the concentration of the element, in moles/mg. of mud; and I_m is the initial mass of the mud, in mg/sq ft. The initial surface loading of the mud can be estimated from

$$I_m = \frac{SM_r(1)I(1)}{(1+S)} \tag{8.43}$$

where S is the solid-to-liquid mass ratio, Mr (1) is the H+1 mass contour ratio, and I (1) is the H+1 ionization rate.

The amount of the element that is associated with the hydrous solids, and that remains on the surface after decontamination, is

$$R_2 = \frac{(e^{-k_f I_m}) I_\ell^2}{K + I_\ell} \tag{8.44}$$

where I_ℓ is the amount of the element not associated with the mud; if I_ℓ is in moles/sq ft, then K is also in moles/sq ft (see Eqs. 8.32 and 8.33).

The amount remaining after decontamination, of the element that is in the liquid phase and that can be chemisorbed by the surface, is

$$R_3 = aI_\ell^n \tag{8.45}$$

where a is now in moles/sq ft.

If the parameters R_M, k_f, K, a, and n are assumed to be known from the decontamination data for the land surface and seawater fallout, and if the interactions in the slurry drop are determined for various elements, then the parameters C_s and I_ℓ can be evaluated. Information on all seven parameters is needed before values of R_1, R_2, and R_3 can be estimated for the harbor type fallout.

8.4.2 Interactions in Slurry Drops: Ionic Species

Two types of interactions with the mud, or soil, particles are considered for the soluble ionic species: (1) two-phase concentration equilibria interactions, and (2) adsorption interaction. In both types of interactions, the soluble ions are assumed not to interact with the hydrous solids to any appreciable degree; an alternate assumption is that the hydrous solids are not present in the slurry fallout.

In the case of the two-phase equilibrium ion-exchange reaction, let m_s be the mass of the solids in the drop and m_ℓ be the mass of the liquid phase in the drop. The equilibrium constant for the exchange reaction, in terms of the mass (i.e., molat) concentrations of an element, is

$$K_1 = Si_3/i_1 \tag{8.46}$$

where i_3 is the number of moles of an element in the liquid phase, i_1 is the number in the solid phase, and S is m_s/m_ℓ, the solid-to-liquid mass ratio. Since the sum of i_1 and i_3 is equal to i, the amount in each phase in a drop of the slurry is

$$i_1 = \frac{Si}{K_1 + S} \tag{8.47}$$

and

$$i_3 = \frac{K_1 i}{K_1 + S} \tag{8.48}$$

If K_1 holds to the point of solution saturation, or to the drying time, for the case in which many drops are deposited on a surface, then i can be replaced with I in moles/sq ft, i_1 with I_m, and i_3 with I_ℓ. The concentration of an element in the solid phase is then

$$C_s = \frac{SI}{(K_1 + S) I_m} \quad \text{moles/mg. of solid} \tag{8.49}$$

and the initial level, for the amount of an element in the liquid phase (i.e., the amount adsorbed on the surface plus the amount left in the soluble crystals), is

$$I_\ell = \frac{K_1 I}{(K_1 + S)} \tag{8.50}$$

The fraction of an element remaining after decontamination, for the two-phase concentration equilibria type of interaction, is

$$F = \frac{aI^{n-1}}{(1 + S/K_1)^n} + \frac{SR_M(1 - e^{-k_f I_m})}{(K_1 + S) I_m} \tag{8.51}$$

In experiments with San Francisco Bay muds, the only element that appeared to decontaminate by this mechanism was iodine.[5] For one core sample of San Francisco Bay mud (sample 20B), the equation that gives good representation of the data is

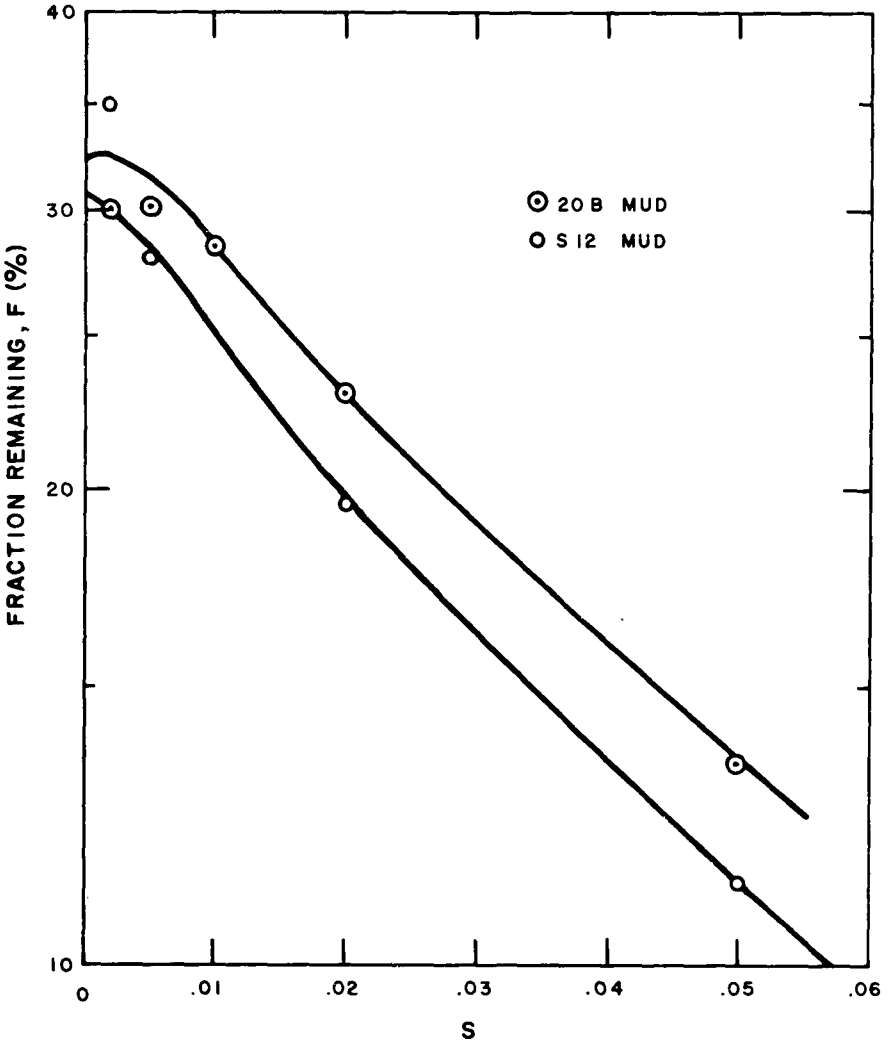
$$F = \frac{0.324}{(1 + S/0.0152)^{0.907}} + \frac{560\, S \left[1 - \exp(-5.78 \times 10^{-4} I_m)\right]}{(0.0152 + S) I_m} \tag{8.52}$$

For another sample of San Francisco Bay mud (sample S12), the equation derived from the data is

$$F = \frac{0.308}{(1 + S/0.0200)^{0.907}} + \frac{220 S \left[1 - \exp(-1.16 \times 10^{-3} I_m)\right]}{(0.0200 + S) I_m} \tag{8.53}$$

The data and computed curves are plotted as a function of S in Figure 8.5. The value of n was taken from Table 8.5. In the experiments, I was held constant; and the total carrier synthetic seawater fallout was used at the 100 C-Level. At the 100 C-Level, some hydrous solids were present in the slurry and were, at least partially, responsible for the high values of F at the lower mud concentrations.

Figure 8.5
FRACTION OF IODINE REMAINING AS A FUNCTION OF THE SOLID-TO-LIQUID RATIO ON NAVY GRAY PAINT SURFACES CONTAMINATED WITH THE SLURRY FALLOUT SIMULANT DECONTAMINATED BY THE IMMERSION STIRRER METHOD



An adsorption reaction of an element with the soil or mud particles may be written, according to the Freundlich adsorption equation, as

$$i_1/m_s = B_o(i_3/V_\ell)^p \tag{8.54}$$

where B_o and p are constants at a given temperature and V_ℓ is the volume of liquid in the drop (or in the bulk slurry solution). For seawater, V_ℓ can be replaced by S/m_s. If all the parameters in Eq. 8.54 are divided by the unit area and if i_1 and i_3 are divided by the initial level to convert to fractions, then Eq. 8.54 becomes

$$(I_1/I)/I_m = B(S/I_m)^p(I_3/I)^p \tag{8.55}$$

where

$$B = B_o I^{p-1} \tag{8.56}$$

The application of Eq. 8.55 over a range of S values is limited by the adsorption capacity of the soil, or mud, particles. The limit, which occurs at low values of S when there are more ions in solution than are required to saturate the mud, is defined as

$$(I_1/I)/I_m = B(max) \tag{8.57}$$

The values of the concentration of an element in the solid phase, of general application, to decontamination are given by

$$C_s = \left[(I_1/I)/I_m\right]_s I \tag{8.58}$$

where the sub s denotes the value of the ratio at a given value of S. The concentrations in the liquid phase are given, in general, by

$$I_\ell = (I_3/I)_s I \tag{8.59}$$

In the experiments carried out with San Francisco Bay mud samples, the only element that exhibited adsorption behavior with the mud was cesium; no data were obtained on other alkali-group elements or on alkaline earth elements. Equilibrium adsorption data for cesium, on some of the slurries, are shown in Figure 8.6.[5] Over the linear portion of the curve, the data are represented by

$$(I_1/I)/I_m = 20.65\left[(S/I_m)(I_3/I)\right]^{0.812} \tag{8.60}$$

for sample 20B, and

$$(I_1/I)/I_m = 0.632\left[(S/I_m)(I_3/I)\right]^{0.579} \tag{8.61}$$

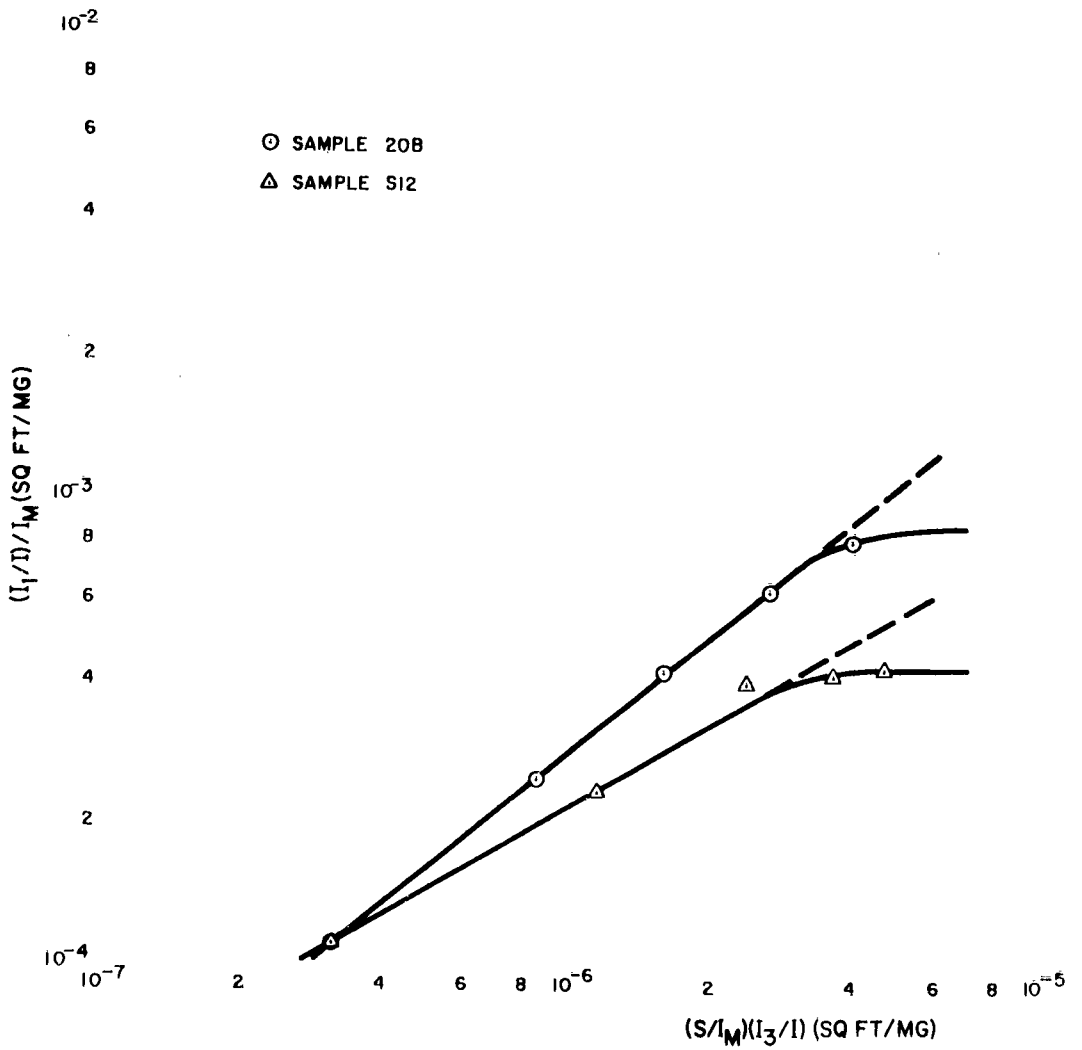
for sample S12. The value of B(max) is 8.4×10^{-4} for sample 20B and 4.2×10^{-4} for sample S12; thus the mud of the 20B sample had an adsorption capacity about twice that of the S12 sample.

In converting the reported adsorption data to express them in terms of a unit area coverage on a contaminated surface, it was assumed that the ratio of the volume of slurry to the area covered by the slurry drop, for all drop sizes, was constant. Since large drops were used in the experiments to obtain the data, the curve of Figure 8.5 is undoubtedly more applicable for a slurry fallout of large drop sizes.

In the above equations, I_m, S, and I are all independent variables; however, when the composition variables from the simple fallout scaling system functions are used in estimating the values of these parameters, I_m is not independent of S and I, for a given radioelement. The unusual form of the adsorption equation variables is due to (1) the definition of I_m, which specifies the amount of soil on the unit area (2) of S, which, with I_m, defines the amount of liquid present in the slurring drop; and (3) of I, which specifies the total amount of the element that is distributed between the two phases. The fraction of an element remaining after decontamination, for the adsorption type of interaction, is

$$F = a(I_3/I)_s^n I^{n-1} + \left[(I_1/I)/I_m\right]_s R_M\left(1 - e^{-k_f I_m}\right) \tag{8.62}$$

Figure 8.6
EQUILIBRIUM ABSORPTION OF CESIUM DATA ON SOLIDS IN SLURRIES OF SAN FRANCISCO BAY MUD SAMPLES



In most cases, the assumption that equilibrium adsorption of an ion onto the mud, or soil, particles occurs throughout the drying stage is not valid. As the concentration of an ion increases in the drying period, its adsorption onto the soil increases (i.e., moves up the adsorption curve) and adsorption values larger than B(max) can actually be obtained. This behavior occurred in the reported decontamination data for the cesium slurries; the data are given in Table 8.12 along with the derived decontamination equation constants and the F values computed by use of Eq. 8.62. For both San Francisco Bay mud samples, I_1/I is unity at an S value of 0.0049. At some mud concentration below this value, all the cesium was adsorbed by the soil particles. At an S value of 0.0019, I_3/I is still 0.15 for the 20B mud and 0.52 for the S12 mud (if the contribution of the first term of Eq. 8.62 to the value of F is negligible).

The values of $(I_1/I)/I_m$ derived from the decontamination data at the lowest mud concentration are considerably higher than those obtained from the equilibrium slurry experiments. For these harbor bottom soils, the cesium turned out to be an excellent tracer for the soil particles. The fraction of the cesium (and soil) after decontamination, for S values larger than 0.0049, is given by

$$F = R_M \left(1 - e^{-k_f I_m}\right)/I_m \qquad (8.63)$$

8.4.3 Interactions in Slurry Drops: Insoluble or Non-reactive Elements

Many of the fission product elements in seawater containing low concentrations of hydrous solid material have essentially no chemical interactions with the soil except that of being physically entrained in the mass of the solid particles. The elements that exhibit this type of behavior in the slurry fallout are those that can form colloidal particles, insoluble hydroxides, or stable adsorption complexes with similar types of small particles.

The entrainment, or mixing, of an element of the insoluble, nonreactive type by the solid particles in a drop, or in a bulk slurry, causes a decrease in the concentration of the element in the liquid phase. If only volume mixing took place in a slurry drop of a given volume containing a given amount of an element, the concentration of the element, in both phases, would remain essentially constant and be independent of the amount of mud particles in the drop. But when a drop lands on a surface, the rapidly settling soil particles entrain, and carry down, additional amounts of the insoluble elements. In this entrainment process, the increase in the depletion of an element in the liquid phase with an increase in the mass of the solids appears to be nearly proportional to the concentration of the element in the liquid phase. Thus, the change in the

Table 8.12

DECONTAMINATION OF CESIUM IN A HARBOR TYPE SYNTHETIC FALLOUT
(SAN FRANCISCO BAY MUD SAMPLES)

R_M (mg/sq ft)	k_f (sq ft/mg)	I_m (mg mud/sq ft)	S	$(I_i/I)/I_m$ (sq ft/mg mud)	F(calculated) (percent)	F(observed) (percent)
Sample 20B						
196	5.38×10^{-4}	0	0	0	--	0.41
		346	0.0019	2.46×10^{-3}	8.19	8.19
		865	0.0049	1.16×10^{-3}	8.42	8.55
		1730	0.0098	5.78×10^{-4}	6.86	6.56
		3460	0.197	2.89×10^{-4}	4.78	4.91
		8650	0.0498	1.16×10^{-4}	2.26	3.66
Sample S12						
146	1.17×10^{-3}	0	0	0	--	0.41
		346	0.0019	1.66×10^{-3}	8.08	8.08
		865	0.0049	1.16×10^{-3}	10.8	10.8
		1730	0.0098	5.78×10^{-4}	7.32	7.18
		3460	0.0197	2.89×10^{-4}	4.14	3.88
		8650	0.0498	1.16×10^{-4}	1.69	1.84

Surface: Navy gray paint

Method: Immersion Stirrer

liquid phase concentration may be approximately represented by

$$\frac{-dC_\ell}{dS} = k_\ell C_\ell \tag{8.64}$$

where C_ℓ is the concentration of an element per unit mass of the (original) liquid and k_ℓ is the mixing coefficient. Integration gives

$$C_\ell = C_o\ e^{-k_\ell S} \tag{8.65}$$

where C_o is the concentration of an element in the liquid phase at S = O.

But since the exponential term gives the fraction of an element in the liquid phase, Eq. 8.65 can be written as

$$C_\ell = i\, e^{-k_\ell S}/m_\ell = iS\ e^{-k_\ell S}/m_s \tag{8.66}$$

The value of I_ℓ is then given by

$$I_\ell = I\, e^{-k_\ell S} \tag{8.67}$$

Similarly, the concentration of an element entrained in the mass of solid particles is

$$C_s = I(1 - e^{-k_\ell S})/I_m \tag{8.68}$$

The amount of an element remaining after decontamination is

$$R = ae^{-nk_\ell S}(I^n) + \frac{I^2\, e^{-(2k_\ell S + k_f I_m)}}{(K + I\, e^{-k_\ell S})} + \frac{R_M I}{I_m}(1 - e^{-k_\ell S})(1 - e^{-k_f I_m}) \tag{8.69}$$

The only data available for testing and evaluating the mixing equation constant are those of Cole, Heiman, and Miller;[5] these data are summarized in Table 8.13. The values of R_M were calculated at the higher mud concentrations where the contribution of the first two terms of Eq. 8.69 (which represent the

Table 8.13

IMMERSION STIRRER DECONTAMINATION OF SOME INSOLUBLE TYPE ELEMENTS IN SLURRIES WITH SAMPLE 20B SAN FRANCISCO BAY MUD FROM NAVY GRAY PAINT SURFACES

S	Ce	Zr(Nb)	Nb	Ru	Te	Np
1. Fraction of Element Remaining After Washing, (F in percent)						
0	68	63	61	77	66	50
0.0019	33	-	-	-	45	33
0.0049	12	26	24	23	-	17
0.0098	12	16	14	10	9.4	5.0
0.0197	4.6	6.7	7.2	5.5	-	2.9
0.0498	3.1	5.6	5.0	4.8	-	1.6
2. Derived Value of R_M of Equation 8.69, (mg/sq ft)						
0.0098	334	445	390	292	262	140
0.0197	186	271	292	222	-	117
0.0498	270	488	436	418	-	140
Average	263	402	373	311	-	132

interaction of an element in the seawater phase with the surface) is very small. For this condition, R_M is approximated by

$$R_M = I_m F/(1 - e^{-k_f I_m}) \tag{8.70}$$

The k_f value used in Eq. 8.70 was the average of those obtained from the data for the soil, iodine, and cesium decontaminations, namely 5.6×10^{-4} sq ft/mg.

Although the values of the fractions remaining are somewhat scattered, they show definitely that, even at low concentrations, the solid particles were the predominating influence on the decontamination effectiveness of a simple water washing procedure. No good explanation can be given for the consistent low F values for Np; however, it was the only element for which no carrier was used with the tracing element. Perhaps, as a +2 ion, it may have adsorped preferentially on the top layers of the soil during the drying process.

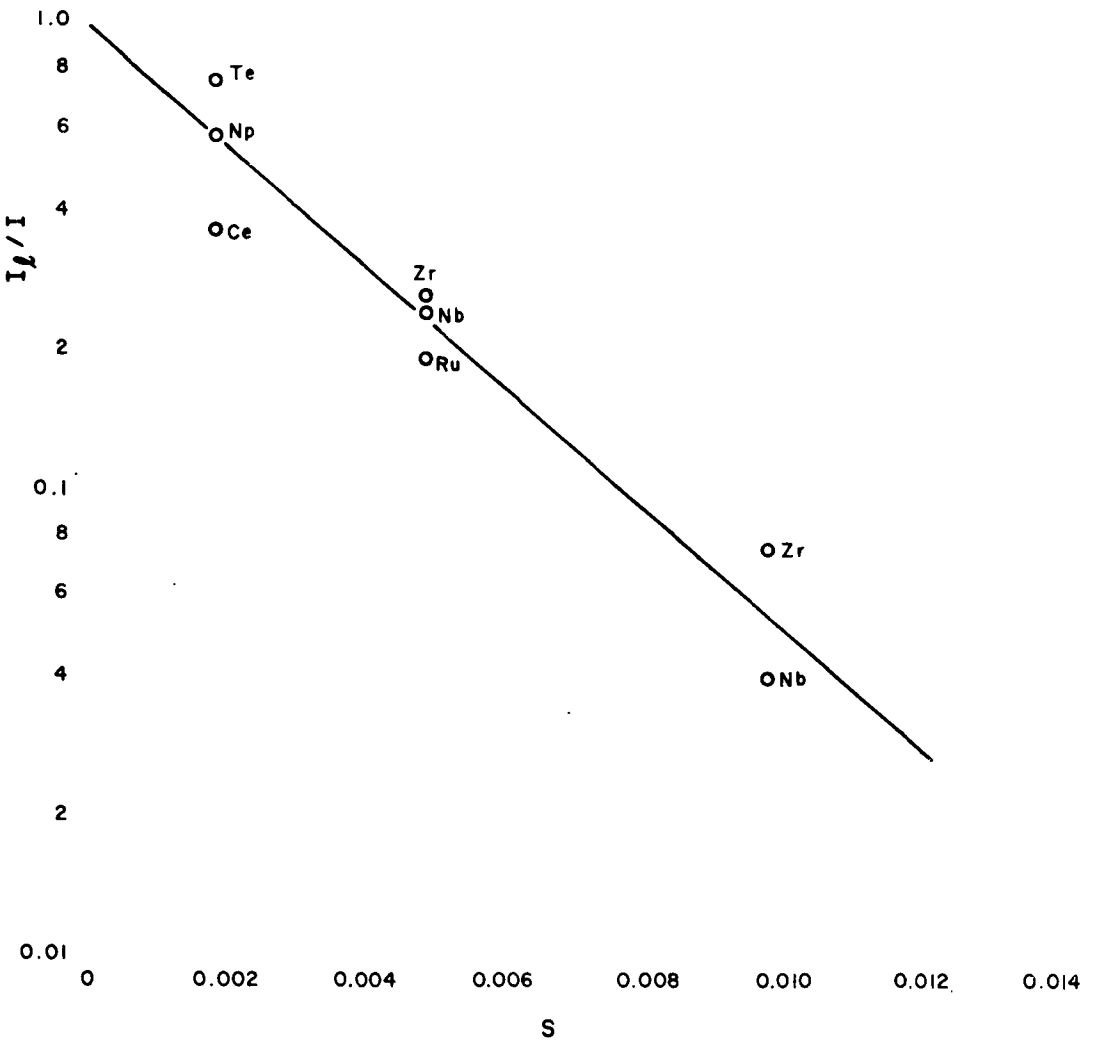
The average value of R_M, including the values for the soil (350) and for cesium (196), but excluding the values for Np, is 320 mg/sq ft. This average value of R_M, the appropriate values of a, n, and K and the F values of Table 8.13 were used with Eq. 8.69 to estimate the term $e^{-k_\ell S}$, or I_ℓ/I, at each slurry composition. The calculated values are shown in Figure 8.7 as a function of S. The line drawn through the points gives a k_ℓ value of 300; thus the derived mixing function is given by

$$I_\ell/I = e^{-300S} \tag{8.71}$$

The mixing function, as derived, actually does not specify when the mixing occurred; it represents, for the set of data from which it was derived, the final mixing with respect to the contamination and decontamination of the surface. The rapid decrease of I_ℓ/I with increasing S suggests that the type of mixing of the insoluble elements with the muds, as represented by Eq. 8.71, would predominate in determining the final distribution of the insoluble elements between the liquid and mud phases, at least with respect to their decontamination interactions. This conclusion, if it is held generally, would alleviate the very difficult problem of determining the distribution of an element among the various phases in a slurry drop, purely on the basis of fireball or cloud chemistry considerations. The data on the decontamination of iodine and cesium also suggest that the interactions in the contamination process predominate in determining their final distribution among the phases.

The rapid change in decontamination behavior from that of a pure seawater fallout to that of a dry land particle fallout with small amounts of soil,

Figure 8.7
VARIATION OF I_ℓ/I WITH S AS DERIVED FROM IMMERSION STIRRER DECONTAMINATION OF SAN FRANCISCO BAY MUD SLURRIES



or mud, particles in harbor fallout simplifies, to a great degree, the harbor fallout decontamination problem. If this is the case generally, then only a very few conditions of detonation can occur that can produce the compositions of fallout that will behave grossly differently in decontamination than the two extreme types; namely, the seawater fallout and the dry land fallout.

8.5 Use of the Decontamination Functions in Estimating Decontamination Effectiveness

8.5.1 Selection of Parameter Values

To illustrate the interrelationships among the many independent and dependent variables of the decontamination equations, a set of hypothetical fallout conditions were selected and the decontamination effectiveness of each, for the simple water washing procedure, were calculated. In addition, the computation serves as a useful technique for combining the fallout system functions and the decontamination functions as well as for indicating how the decontamination effectiveness may depend on the detonation variables. The simple water washing decontamination procedure was selected because it is the only procedure for which sufficient data have been obtained for the use in such a computation.

The detonation conditions selected for the computations were: (1) a land surface detonation; (2) a seawater surface detonation; and (3) a surface detonation for a water depth of 50 feet. A weapon yield of 1-MT was selected for each condition; for these detonations, the values of S_{ι} and $M_{\tau}(1)$ are given in Tables 6.7 and 6.8. In the computation it was assumed that the same fallout pattern (in r/hr at 1 hour) occurs for all three detonations so that, for a 15 mph wind speed, the same values of I(1) fall at the same downwind distance. Therefore, no adjustment was made for possible differences in fractionation of the radioactive elements with distance or for possible, and unknown, differences in particle size distributions in the fallout from each of the detonations.

In the computations, the water-washing decontamination system, for the described fallout conditions, is a highly idealized system with respect to a real practical system because: (1) the data were obtained by use of clean Navy grey paint surfaces and (2) large excesses of water during decontamination. However, the data and computations should apply to other painted or smooth nonporous surfaces, such as asphalt, so this aspect of the idealization should not restrict the application of computational results to real decontamination systems.

The large excess of water used in the laboratory experiments probably resulted in the lowest possible F value in the decontamination of a given contamination; such excesses of water could not be used in a practical system. On the other hand, the same F values probably could be realized by repeated

applications of lesser amounts of water; thus the computed F values should indicate the limiting, or lowest, achievable residual value of the amount of fallout remaining after decontamination. This limiting value of F, achieved only with excessive amounts of water, or with a very large amount of work, is called the infinite-effort decontamination effectiveness.

For surfaces contaminated with a heavy deposit of particles, water-washing without high pressures would take a long time and large excesses of water to clear off a large area because of the pile-up of the particles downstream. The idealized computation does not consider such practical conditions as these because they are not included in the data. The data do, however, indicate the action of the water, through dissolution and through surface tension forces, in loosening and removing an ion or particle from the surface.

The transport of the fallout materials from one location to another is outside the context of the surface interaction considered here; that aspect of fallout decontamination is discussed in Chapter 9. It is valuable, however, to know the limit to which a fallout material can be removed from a surface. Then it is possible to judge whether the effectiveness of a practical method, with a given amount of applied effort, is within a reasonable factor of the limit.

8.5.2 Decontamination of Fallout From the Land Surface Detonation

The decontamination by simple water washing of the particle-type fallout from a land surface detonation is described by

$$R_r(1) = \underset{r/hr \text{ at } 1 \text{ hr}}{\left[320/M_r(1)\right]\left[1-\exp(-5.7\times10^{-4}y)\right]} \qquad (8.72)$$

where

$$y = M_r(1)I(1) \quad \text{mg fallout/sq ft} \qquad (8.73)$$

The value of $M_r(1)$ is estimated from the functions given in Chapter 6 (see Volume I) that describe, in a gross way, its dependence on both the fractionation of the radionuclides and the specific activity of the fallout particles. The use of the single value of 320 mg/sq ft for R_M, as previously mentioned, neglects the dependence, if any, of R_M on particle size. The data of Tables 8.1 and 8.2 for the immersion stirrer decontamination of prewetted soils indicate that R_M should increase with decreasing particle size, but no function for describing this dependence can be derived from the data. The values of both R_M and k_f were found to be sensitive to prewetting; the values of these parameters in Eq. 8.72, as obtained from the slurry experiments, include the effect of prewetting.

The computations for $R_r(1)$, the remaining radiation rate after decontamination, decay-corrected to H+1, and the fraction of radiation remaining, $F_r(1)$, are summarized in Table 8.14 with other pertinent parameters. The time after detonation of the decontamination is not specified; hence the computation assumes no significant redistribution of the fallout particles by wind or rain but it does assume, as mentioned above, overnight high-humidity wetting of the particles. The effect, on the decontamination effectiveness, of fractional surface loading and of the increase of the specific activity of the fallout with particle size and/or distance are shown by the general increase of $F_r(1)$ with downwind distance. The highest residual radiation level remaining after water washing, from the combination of the fallout model and decontamination interrelationships, is located between 38 and 76 miles downwind. The highest values of $F_r(1)$ occur at the farthest downwind distances where the smaller fallout particles land.

8.5.3 Decontamination of Fallout from the Seawater Surface Detonation

Since each radioelement in seawater fallout may interact with the surface, and decontaminates independently, the fraction of each element in the fallout remaining after decontamination must be calculated to estimate, by summing, the gross total ionization rate of the remaining mixture of radionuclides. Because each element in the fallout has a different degree of retention by the surface, the radioactive mixture is altered or fractionated in the simple water-washing decontamination process. The gross decay of the radioactivity on the surface after decontamination therefore will not be the same as the decay of the undisturbed original fallout. Accordingly, value of F_r itself is not a true or valid measure of the effectiveness of decontamination of seawater fallout with regard to the reduction of the exposure dose. The most valid measure of the effectiveness is given by the ratio of the exposure dose with use of the countermeasure to the potential exposure (as discussed in Section 8.3.5). The value of the ratio depends on both the time of decontamination and time after decontamination of the exposure period.

The relative amounts of radioelements left on the surface after decontamination are represented by the sum

$$R = \Sigma_j R_j \tag{8.74}$$

where j is the designation for an element. From Eq. 8.33, R_j is given by

$$R_j = a_j I^{nj} + \frac{I^2}{K_j + I} \tag{8.75}$$

Table 8.14

ESTIMATED DECONTAMINATION EFFECTIVENESS FOR FALLOUT FROM A 1-MT YIELD LAND SURFACE DETONATION[a] AT SEVERAL DOWNWIND DISTANCES[b]

X (miles)	I(1) (r/hr at 1 hr)	$M_r(1)$ $\left(\frac{\text{mg/sq ft}}{\text{r/hr at 1 hr}}\right)$	y (mg/sq ft)	$R_r(1)$ (r/hr at 1 hr)	$F_r(1)$ (percent)
1.9	9800	133.	1,300,000	2.4	0.024
3.8	9800	31.7	310,000	10.1	0.104
5.7	3140	14.3	45,000	22.4	0.71
7.6	930	10.4	9,670	30.6	3.29
9.5	284	8.32	2,360	28.2	9.93
15.	1610	10.2	16,400	31.4	1.95
19.	1820	7.83	14,300	40.9	2.25
38.	1840	4.45	8,190	70.4	3.83
76.	500	2.59	1,300	63.8	12.8
114.	138	1.95	269	23.0	16.7
152.	38	1.58	60	6.7	17.6
190.	10	1.35	14	1.9	19.0

a. 100 percent fission, B = 1

b. Water washing of smooth horizontal surfaces

In lieu of data on the dependence of the values of a, n, and K on the time of contact for each element, the data of Table 8.8 are used here for all elements, in the form

$$a_j(\tau) = a_j \tau^{-0.051} \tag{8.76}$$

$$n_j(\tau) = n_j + 0.0006\tau \tag{8.77}$$

and

$$K_j(\tau) = K_j \tau^{-0.055} \tag{8.78}$$

where τ is the time of contact in days; the values of the coefficients, a_j and K_j are for $\tau = 1$ day.

Use of the original equation constants derived from the reported data requires a conversion of I from the C-Level units to I(1) in r/hr at 1 hour to obtain the equivalent H+1 value of R_j. Also required is a similar conversion of a_j and K_j. Because the C-Level unit is based on a given relative concentration of the important fission product elements, it is convenient to make the conversion to I(1) for Eq. 8.75 rather than for the individual ionization rate contributions from each element. This selection of procedure assumes that the relative amounts of each element present in the fallout does not change much with the initial level, I(1), over the time period for which the computations are made. The pertinent information for this conversion are that (1) the 1 C-Level corresponds to a concentration of 5.6×10^{-9} moles of fission products per liter of seawater and (2) 0.3 milliliters of that solution, as used in the decontamination experiments covered 0.25 sq in of surface area. Hence the surface density of the fission products was 9.68×10^{-10} moles/sq ft per C-Level.

The ratio, I/I(1), in terms of r/hr at 1 hour is obtained by dividing the fission product surface density per C-Level into the fission product contour ratio, $FP_r(1)$. From Eq. 6.40, for the standard values of D(1), q_x, $i_{fp}(1)$, and $i_j(1)$, the ratio is then given by

$$I/I(1) = \frac{8.79 \times 10^{-3} \Sigma_j A r_j A(\alpha)}{(r'_\alpha(1) + 0.019)} \text{ C-Level units/(r/hr at 1 hr)} \tag{8.79}$$

In this illustrative computation, the loss of the elements Kr and Xe at H+1 from the deposited fallout was assumed. When this assumption is applied both $\Sigma_{jA} r_{jA}(\alpha)$ and $r'_{\alpha}(1)$ are 0.91; the value of the ratio I/I(1) is then 8.60×10^{-3}

Because the fraction of an element remaining after decontamination in either set of units must be the same at a given surface density of atoms, the conversion of constant a_j from C-Level units to 4/hr at 1 hour units is given by

$$a_{rj} = a_j \left[I/I(1)\right]^{nj-1} \tag{8.80}$$

The value of K_j depends on the mass of the warhead, bomb, or target material that becomes mixed with the radioelements and seawater in the fallout. For conversion of the original data to other concentrations of these materials, the K_j in C-Level units was converted to the mass of the metallic element per unit area by multiplying the original K_j values by the number of milligrams of Fe plus Al per sq ft per C-Level used in the experiments. The conversion is given by

$$K^*_{cj} = 0.133 K_j (\text{mg Fe+Al})/\text{sq ft} \tag{8.81}$$

The conversion of K^*_{cj} to r/hr at 1 hour units is done by dividing K^*_{cj} by the bomb mass and by the fraction-of-device contour ration, $FD_r(1)$, giving

$$K_{rj} = \frac{K^*_{cj}}{M_B FD_r(1)} \quad \text{r/hr at 1 hr} \tag{8.82}$$

where M_B is the mass of the warhead in terms of the mass of metal and $FD_r(1)$, from Eq. 6.42 is

$$FD_r(1) = \frac{1.83 \times 10^{-11}}{BW \left[r'_{\alpha}(1) + 0.019\right]} \quad \begin{matrix}(\text{r/hr at} \\ 1 \text{ hr-sq ft})^{-1}\end{matrix} \tag{8.83}$$

Using the values B = 1, W = 10^3, and $r_{\alpha}(1) = 0.91$, $FD_r(1)$ is 1.97×10^{-14} (r/hr at 1 hour sq ft)$^{-1}$. For the computation, it was assumed that the mass of the warhead and/or missile was 10 tons (9.1×10^9mg). The product, $M_B FD_r(1)$, is then 1.79×10^{-4} (mg/sq ft)/(r/hr at 1 hour). The use of the product, $M_B FD_r(1)$, in Eq. 8.81 assumes uniform mixing of the mass M_B with the radioactive elements.

The values of the constants a_j, n_j, and K^*_{cj} in C-Level units and their values in r/hr at 1 hour units, for all the elements considered in the calculations, are summarized in Table 8.15. Some of the values in Table 8.15

differ from those of Table 8.5, and many values have been estimated. The values in Table 8.15 that differ from those in Table 8.5 were selected on the basis of intercomparisons of all the decontamination data obtained at the 100 C-Level on the expected relative chemical behavior of the different elements in seawater media. The 6.7-day values of the constants were computed for an assumed decontamination time of 6.7 days after detonation as well as a contact time of 6.7 days.

The correction of a_j and K_j to ionization rate units also converts R_j to R_{rj} (or F_{rj}, the fraction remaining) of the jth element. To obtain the magnitude of the ionization rate remaining, or its fraction of the initial level, of all the radioelements in the fallout mixture, the values of R_j for each element must be weighted according to the percentage it contributes to the total gamma radiation. Otherwise the R_{rj} gives the radiation rate remaining for the case in which I(1) is entirely due to the jth element. Multiplying the F_{rj} or R_{rj} values by the fractional contribution of element j to the total gamma radiation gives its contribution to the total amount remaining. The total, or summed, ionization rate remaining after decontamination is then given by

$$R_r(\tau) = \Sigma_j P_j(t) R_{rj}(\tau) \quad \text{r/hr at 1 hr} \tag{8.84}$$

where τ is the contact time and t is the time after detonation. In Table 8.15 t and τ are taken as being the same time. The values of P_j(6.7d) were taken from Miller and Loeb's calculation for U-235 fission products.[3] Estimates of P_j for the fission products from other types of fission and fissile nuclides have not been made.

The N_p contribution was computed on the assumption that the 0.019 fractional excess in the unit fission product ionization rate at H+1 was entirely due to U-239 induced activity. At 6.7 days the ionization rate from this relative amount of N_p is about 1.4 times the ionization rate from the fission products.

The sum of the P_j values in the table was adjusted to unity. Except for the rare gas Xe, which contributes only about 1.5 percent at the time, the remaining unlisted fission product elements contribute only 0.22 percent to the gross fission product ionization rate. The chief contributors are I, La, and Np; together these three elements contribute 82 percent of the total ionization rate.

The values of $P_j R_{rj}$, by element, for the first term of Eq. 8.75 and their sums, for selected values of I(1), are shown in Table 8.16. The sums of $P_j R_{rj}$ for the second term of Eq. 8.75 are included also; they indicate that, even with the 10 ton warhead, the contributions from the second term are extremely small except at the very high values of I(1). The calculated fractions of the

Table 8.15

SUMMARY OF IMMERSION STIRRER DECONTAMINATION EQUATION CONSTANTS AND IONIZATION RATE WEIGHTING FACTORS (IN C-LEVEL UNITS FOR 1 DAY CONTACT, AND IN R/HR AT 1 HR UNITS FOR 6.7 DAY CONTACT TIME)

Decontamination Equation Constants at τ = 1 day (C-Level Units)					Decontamination Equation Constants at τ = 6.7 days (r/hr at 1 hr)			Ionization Rate Weighting Factors at 6.7 days (%)	
Element	a_j	n_j	K_j	K_j*	a_{rj}	n_j	K_{rj}	P_j (6.7d)	
Rb	0.018	0.50	175,000	23,300	-	-	-	-	
Sr	0.075	0.85	1120	149	-	-	-	-	
Y	0.75	0.95	570	76	0.86	0.95	3.8×10^5	0.01	
Zr	0.75	0.93	1010	134	0.94	0.93	6.8×10^5	2.30	
Nb	0.68	0.94	950	126	0.82	0.94	6.3×10^5	0.97	
Mo	0.7	0.90	1000	133	1.03	0.90	6.7×10^5	1.85	
Tc	0.7	0.90	1000	133	1.03	0.90	6.7×10^5	0.26	
Ru	0.78	0.92	320	43	1.04	0.92	2.2×10^5	1.33	
Rh	0.78	0.92	320	43	1.04	0.92	2.2×10^5	0.19	
Sb	0.7	0.90	350	47	1.03	0.90	2.3×10^5	0.20	
Te	0.68	0.90	300	40	0.99	0.90	2.0×10^5	2.61	
I*	0.40	0.80	1000	133	0.94	0.80	6.7×10^5	26.57	
Cs	0.018	0.50	175,000	23,300	-	-	-	-	
Ba	0.080	0.85	1050	140	0.15	0.85	7.0×10^5	2.14	
La	0.78	0.98	620	82	0.78	0.98	4.2×10^5	26.32	
Ce	0.79	0.94	650	86	0.95	0.94	4.3×10^5	2.33	
Pr	0.79	0.94	650	86	0.95	0.94	4.3×10^5	0.05	
Nd	0.82	0.93	620	82	1.04	0.93	4.2×10^5	0.99	
Pm	0.82	0.93	620	82	1.04	0.93	4.2×10^5	2.88	
Np	0.60	0.88	510	68	0.96	0.88	3.4×10^5	29.00	
								Sum 100.00	

*Add 0.21 at 7 days, 0.30 at 14 days.

Table 8.16

CALCULATED VALUES OF THE IONIZATION RATE REMAINING AFTER DECONTAMINATION AT 6.7 DAYS AFTER DETONATION FOR SIMPLE WATER WASHING OF SMOOTH HORIZONTAL SURFACES

Element	I(1) (r/hr at 1 hr)						
	10	30	100	300	1,000	3,000	10,000
1. $P_j a_{rj} \left[I(1)\right]^{n_j}$ in r/hr at 1 hr							
Y	0.0008	0.002	0.007	0.019	0.061	0.17	0.54
Zr	0.185	0.502	1.57	4.36	13.4	37.2	114.0
Nb	0.068	0.194	0.62	1.69	5.25	14.7	45.6
Mo	0.150	0.404	1.20	3.20	9.54	25.6	75.5
Tc	0.021	0.056	0.17	0.45	1.34	3.60	10.6
Ru	0.111	0.315	0.94	2.62	8.71	21.7	72.5
Rh	0.016	0.045	0.14	0.37	1.14	3.11	9.4
Sb	0.016	0.044	0.13	0.34	1.03	2.77	8.2
Te	0.204	0.550	1.64	4.36	13.0	34.9	103.0
I	2.13	5.47	15.5	40.7	118.0	319.0	952.0
Ba	0.022	0.058	0.16	0.41	1.14	2.89	8.0
La	1.96	5.75	18.7	55.0	179.0	525.0	1710.0
Ce	0.192	0.540	1.71	4.71	14.6	40.9	128.0
Pr	0.0041	0.011	0.036	0.10	0.31	0.87	2.7
Nd	0.088	0.243	0.75	2.07	6.35	17.6	54.0
Pm	0.255	0.707	2.17	6.02	18.5	51.2	158.0
Np	2.11	5.54	16.0	42.1	121.0	320.0	920.0
Sum	7.532	20.43	61.44	168.5	512.4	1421	4372
2. Sum of $P_j I^2(1) / \left[K_{rj} + I(1)\right]$ in r/hr at 1 hr							
Sum	0.00023	0.0021	0.0234	0.211	2.34	20.9	229
3. Gross Radiation Rate and Fraction Remaining After Decontamination							
$R_r(1)$	7.53	20.43	61.46	168.7	514.7	1442	4601
$F_r(1)$	75.3	68.1	61.5	56.2	51.5	48.1	46.0

ionization rate remaining after decontamination, for the seawater fallout, are substantial fractions of the initial deposit levels. The fraction remaining is about 75 percent at the initial level of 10 r/hr at 1 hour level; it decreases to 46 percent at the initial level of 10,000 r/hr at 1 hour.

Although it was stated previously that these computations should give lower limits of the amounts of fallout remaining after decontamination by water washing, fractions of the radiation rate remaining that lie within the range of values given in Table 8.16 have been obtained in decontamination experiments with firehosing techniques on ships surfaces contaminated with seawater fallout in the Pacific Proving Grounds.[10] The limiting fraction values or radiation rate remaining for firehosing, however, should be somewhat smaller than those for simple water washing because of the energy of the impacting water. The field test data at least confirm the general magnitude of the computed fractions of the radiation rate remaining for the simple water washing procedure.

In calculating the amounts of iodine not removed from the surface, the suggested 21 percent additional fraction of the element remaining was included on the assumption that the surface was painted and that this additional fraction remaining was due to chemical reaction with the paint. The additional 21 percent fraction does not take part in any decontamination reaction that does not remove the paint.

The ionization rates, and their fractions of the initial level, remaining are given at various downwind distances in Table 8.17. The major cause of the variation of $F_r(1)$ with downwind distance is the adsorption equilibrium that is established between the surface and the different radioelements in the drops of the saturated salt solution. The calculations assume that the same equilibrium is reached in 6.7 days whether fallout arrived in the form of liquid drops or as a crystal slurry (i.e., saturated solution containing salt crystals).

8.5.4 Decontamination of Fallout From the Seawater Surface Detonation in A Harbor With A Water Depth of 50 Feet

The computation of the $F_r(1)$ values for a harbor-type fallout utilizes the most generalized form of the decontamination functions; some of these are discussed below.

The P_j values of Table 8.15 indicate that, for the slurry-type fallout, two types of interactions should be considered: (1) the interaction behavior for iodine, and (2) the mixing function for insoluble type elements. It could be argued that only the latter need be considered because the iodine present at 6.7 days is a daughter of Te and the latter would be classed as an insoluble type element. This would more certainly be the case, perhaps, if the deposit evaporated

Table 8.17

ESTIMATED DECONTAMINATION EFFECTIVENESS FOR FALLOUT FROM A 1-MT YIELD SURFACE SEAWATER DETONATION AT SEVERAL DOWNWIND DISTANCES[a]

X (miles)	I(1) (r/hr at 1 hr)	$R_r(1)$ (r/hr at 1 hr)	$F_f(1)$ (percent)
1.9	9800	4520	46.1
3.8	9800	4520	46.1
5.7	3140	1510	48.0
7.6	930	480	51.6
9.5	284	160	56.3
15	1610	802	49.8
19	1820	902	49.6
38	1840	911	49.5
76	500	270	54.0
114	138	82	59.7
152	38	25	66.5
190	10	7.5	75.3

a. Water washing of smooth horizontal surfaces

to dryness and remained that way. In the described computations, however, the more humid conditions permitting movement of the iodine to the surface is assumed. The treatment of the decontamination of the insoluble type elements includes the case where the deposit has evaporated to dryness and all the elements decontaminate as if mixed with harbor bottom material.

In using the equations for the decontamination of the slurries it is convenient to separate the mathematical description of the decontamination process into two parts for estimating the remaining ionization rate levels: (a) the solution interactions and (b) the solid interactions. The designation for this separation is

$$R_r(\tau) = R_{rs}(\tau) + R_{r\ell}(\tau) \tag{8.85}$$

For the general case of the elements in the slurry fallout, the first term of Eq. 8.85 is

$$R_{rs}(\tau) = \frac{C_s R_m \left(1 - e^{-k_f I_m}\right)}{FP_r(1)} \tag{8.86}$$

in which

$$I_m = \frac{M_r(1)SI(1)}{(1 + S)} \tag{8.87}$$

and C_s is the concentration in the solid phase of the slurry in moles of fission products per gram of solids and $FP_r(1)$ is the fission product contour ratio. This designation for the decontamination of the elements in the solid phase is satisfactory if no fractionation is considered and only one type of interaction occurs.

It is more convenient to redefine C_s and compute the fractions of the elements remaining after decontamination for each type of interaction separately. In this way some unit conversions are eliminated since the fraction remaining is the same with all units of measure. For the iodine reaction, the concentration in ionization-rate units is

$$C_{rs}(1) = \frac{SP_j(t)I(1)}{(K_1 + S)I_m} \quad \frac{\text{r/hr at 1 hr}}{\text{mg solids/sq ft}} \tag{8.88}$$

and, for the insoluble elements, it is

$$C_{rs}(1) = (I(1)/I_m)\left(1 - e^{-k_\ell S}\right)\Sigma_j P_j(t) \qquad \frac{\text{r/hr at 1 hr}}{\text{mg solids/sq ft}} \tag{8.89}$$

The value of I_ℓ for each type of interaction is defined, in a similar way, by

$$I_\ell(1) = \frac{K_1 I(1) P_j(t)}{(K_1 + S)} \tag{8.90}$$

for iodine, and

$$I_\ell(1) = I(1)\, e^{-k_\ell S}\ \Sigma_j P_j(t) \tag{8.91}$$

for the insoluble elements.

Also for the general case, the second term of Eq. 8.85 is

$$R_{r\ell}(\tau) = \Sigma_j P_j(t) R_{rj}(\tau) \tag{8.92}$$

where

$$R_{rj}(\tau) = a_{rj}(\tau)\left[I_{r\ell}(1)\right]^{n_j(\tau)} + \frac{e^{-k_f I_m} I^2_{r\ell}(1)}{K_{rj}(\tau) + I_{r\ell}(1)} \tag{8.93}$$

If the two reaction types are separated and converted to fractions, the iodine decontamination ratio is given by

$$F_I = \frac{0.94[I(1)]^{-0.20}}{(1 + 55.5S)^{0.80}} + \frac{SF_m}{(0.018 + S)I_m} + \frac{0.0038}{(0.018 + S)} \tag{8.94}$$

in which K_1 is taken as 0.018 from Eqs. 8.51 and 8.52. The last term is 0.21 times the fraction in the liquid phase to account for the reaction of the iodine with the paint up to 6.7 days. The value of F_m, the fraction of the solids remaining after decontamination, is given by

$$F_m = 320\left[1 - \exp(-5.6\times10^{-4} I_m)\right] \tag{8.95}$$

The fraction of the insoluble elements remaining, from Eq. 8.69, is

$$F_{IE} = \frac{R_{r\ell}(\tau)}{I(1)\Sigma_j P_j(t)} + F_m \left[1-\exp(-300S)\right] \qquad (8.96)$$

The gross fraction of the ionization rate, corrected to H+1, remaining after decontamination is

$$F_r(1) = 0.266F_I + 0.734F_{IE} \qquad (8.97)$$

in which the weighting factors are obtained from the P_j (6.7d) values of Table 8.15.

The computations of the fractions and the levels of the H+1 ionization rates remaining are summarized in Table 8.18. Although the S values indicate that the slurry-type fallout from the selected detonation condition would contain only a few percent of soil by weight, the decontamination ratio, or fraction remaining, of the insoluble elements is the same as that of the soil up to a distance of about 76 miles downwind. For the assumed wetted condition of the fallout deposits at downwind distances more than about 15 miles, slightly over half of the calculated ionization rates remaining after decontamination is due to the remaining iodine. For an assumed dry condition of the deposited particles, $F_r(1)$ would be the same as F_{IE}; in this case, the decontamination ratio for the harbor fallout would almost be the same as the dry-land fallout, except for the increased specific activity of the remaining particles. The major influence of the water in the harbor detonation fallout on the ionization rate(s) remaining after decontamination apparently is to provide a mechanism for increasing the apparent specific activity of the solid mud, or soil, particles. The irregular variation of $F_r(1)$ and of $R_r(1)$ with downwind distance, follows the trend in the I(1) values.

The downwind variations in the fallout pattern with regard to the magnitude of the surface density of the particles, their specific activity and sizes, and the various interactions considered in the previous paragraphs suggest many reasons for the difficulties encountered in interpreting the results of past field test experiments in decontamination. The main cause of the difficulties is that data are not available for establishing the initial state of the chemical systems to which the decontamination results apply. Because the initial conditions of contamination for the decontamination experiments carried out at nuclear weapons tests have not yet been satisfactorily established and because specification of these initial conditions is required to interpret the experimental results, the available decontamination data from those experiments are not included in this chapter. However, even without detailed technical analyses and interpretation, the data and experience obtained at field tests contribute significantly to the

understanding of fallout decontamination operations. In addition to the authors previously cited, significant contributions, in carrying out the early work at field tests, were made by Maloney, [17], [18] Dhein, [18] Molumphy and Bigger, [19] and Hawkins. [20]

Table 8.18

ESTIMATED DECONTAMINATION EFFECTIVENESS FOR FALLOUT FROM A 1-MT YIELD DETONATION ON THE SURFACE OF WATER 50 FEET DEEP AT SEVERAL DOWNWIND DISTANCES[a]

X (miles)	I(1) (r/hr at 1 hr)	S	$M_r(1)$ $\left(\frac{\text{mg/sq ft}}{\text{r/hr at 1 hr}}\right)$	I_m (mg solid/sq ft)	F_m (percent)	F_I (percent)	F_{IE} (percent)	$F_r(1)$ (percent)	$R_r(1)$ (r/hr at 1 hr)
1.9	9800	0.177	82.7	122,000	0.26	4.3	0.26	1.3	128
3.8	9800	0.094	76.8	64,600	0.50	7.3	0.50	2.3	225
5.7	3140	0.066	75.0	14,600	2.2	11.7	2.2	4.7	148
7.6	930	0.057	74.2	3,720	7.5	18.4	7.5	10.4	97
9.5	284	0.049	73.6	976	13.8	26.2	13.8	17.1	49
15	1610	0.056	74.2	6,330	4.9	15.7	4.9	7.8	126
19	1820	0.048	73.6	6,140	5.0	16.7	5.0	8.1	148
38	1840	0.036	72.4	4,630	6.4	19.9	6.4	10.0	184
76	500	0.023	71.5	804	14.4	34.0	14.5	19.7	98
114	138	0.016	71.2	155	17.3	40.3	17.7	23.7	33
152	38	0.013	71.0	35	17.8	49.4	18.4	26.6	10
190	10	0.011	71.0	7.7	17.9	60.4	20.0	30.8	3.1

a. Water washing of smooth horizontal surfaces at 6.7 days after detonation

CHAPTER 8 REFERENCES

1. Heiman, W.J., Contribution of Different Chemical Elements to the Rate of Gamma Radiation at Various Times After an Underwater Burst, USNRDL-387 (1953); J. Colloid Sci 13, 329 (1958).

2. Miller, C.F., Gamma Decay of Fission Products From The Slow-Neutron Fission of U-235, USNRDL-TR-187 (1957).

3. Miller, C.F., and P. Loeb, Ionization Rate and Photon Pulse Decay of Fission Products From The Slow-Neutron Fission of U-235, USNRDL-TR-247 (1958).

4. Miller, C.F., Theory of Decontamination, Part I, USNRDL-460 (1958).

5. Cole, R., W.J. Heiman, and C.F. Miller, Effect of Harbor Bottom Material on the Decontamination of Various Elements in a Synthetic Seawater Contaminant, USNRDL-TR-43 (1955).

6. Lane, W.B., and J. Mackin, unpublished data, USNRDL (1957).

7. Adams, C.E., N.H. Farlow, and W.R. Schell, Geochimica et Cosmochimica Acta, 18, 42 (1960).

8. Miller, C.F., R. Cole, and W.J. Heiman, An Investigation of Synthetic Contaminants for An Atomic Burst In Deep Seawater, USNRDL-411, classified (1953).

9. Bolles, R.C., and N.E. Ballou, Calculated Abundances of U-235 Fission Products, USNRDL-456 (1956).

10. Miller, C.F., R. Cole, R.K. Fuller, L.J. Graham, W.B. Lane, M. Nuckolls, J.F. Pestaner, and P. Sam, Influence of Some Decontamination Conditions and Methods on Decontamination Ratios, USNRDL-441 (1953).

11. Miller, C.F., R. Cole, W.J. Heiman, and M. Nuckolls, Decontamination of Fission Products and Other Atomic Bomb Detonation Debris, USNRDL-439 (1953).

12. The Radiological Recovery of Fixed Military Installations, NAVDOCKS TP-PL-13, revised (1958).

13. Miller, C.F., and M.J. Nuckolls, Decontamination of FP and other ABD Debris from Several Surfaces, USNRDL-TM-53 (1956).

14. Lane, W.B., unpublished data, USNRDL (1960).

15. Miller, C.F., Response Curves For The USNRDL 4-pi Ionization Chamber, USNRDL-TR-155 (1957).

16. Owen, W.L., Standard Recovery Procedures For Tactical Decontamination of Ships, Operation Redwing WT-1323, (1958).

17. Maloney, J.C., W.J. Carr, R. Rexroad, F.S. Badger, Interim Report, Gross Decontamination Study Army Chemical Center Report CRLIR 24 (1951) (classified).

18. Maloney, J., E. Dhein, et al, Decontamination and Protection. Operation Castle WT-928 (1955).

19. Molumphy and Bigger , . Proof Testing of AW Ship Countermeasures, Operation Castle WT-927, classified, (1956).

20. Hawkins, M.B., et al, Radiological Hazards to Ships, Operation Wigwam WT-1032 (1959).

Chapter 9

PRINCIPLE OF DECONTAMINATION EFFICIENCY

9.1 The Concept of Decontamination Efficiency

The concept of efficiency in operations or processes is not new. However, for operations involving the handling and disposing of radioactively contaminated objects, efficiency concepts were, in general, developed and applied rather slowly. In many such operations, efficiency is still not considered. This lack of concern and interest in operational efficiency of decontamination procedures was, in the main, due to the rigid enforcement of "rad-safe" concepts and standards, and of rules and regulations set down for the workers in industries and installations where radioactive materials were handled in routine operations or experiments.

Thus, within the constraints of the "rad-safe" operating rules, the emphasis of the work in cleaning contaminated equipment, laboratory benches, or spills on any surface was to remove as near to 100 percent of the radioactivity as possible. In other words, the effectiveness of a decontamination procedure, rather than the amount of work or energy required to remove the contamination to a specified level, was usually considered in evaluating and in conducting decontamination operations.

Where safety-first principles are appropriate, and where the contaminated areas are small, the emphasis on decontamination effectiveness is usually adequate. In event of a nuclear war, however, rules and regulations set down for peacetime uses of radioactive materials would be abrogated by the detonation of a nuclear weapon. An uncontrolled release of radioactive material in the form of fallout over larger areas of the country, therefore, would require replacing the operating rules based on the safety-first concepts with other types of operational guidance based on the nature of the resulting over-all hazard environment.

Since a large range in the radiological hazards from fallout in a nuclear war is possible, the guidance criteria for exposure doses in carrying out operations must be based on considerations of the biological consequences for a range of such doses. The guidance criteria, in this case, are then derived from information relating the exposure dose to the biological effects of exposure to gamma radiation, with respect to (1) lethality, (2) radiation sickness,

or (3) a range of less severe biological responses. The concept of using an "allowed", or "planning," radiation exposure dose to determine the effectiveness requirements of radiological countermeasures was derived by Strope[1,2] and Laurino[1,3] from considerations of relationships between biological effects and exposure doses.

The planning dose criteria differ from those of a maximum permissible dose limit in that the allowed exposure dose is based on both the degree of the radiological hazard and the priority of an operation. In radiological defense, particularly with regard to decontamination operations, use of the planning dose resulted in two important findings:

1. The lower limit of the required decontamination effectiveness, or of any countermeasure effectiveness, is always some number greater than zero; in some cases, the required effectiveness is small enough that no decontamination process or other protection from the radiological hazard is needed.

2. The combination of (a) the planning dose, (b) the decontamination effectiveness, and (c) the amount of time required to carry out the decontamination process determines the time after detonation when operations of any kind may be resumed.

The first of these findings permits consideration of the use of many decontamination methods that remove less than 100 percent of the fallout from surfaces. The second finding led to the consideration of the working time as an important parameter in large-scale decontamination of a variety of exposed surfaces.

The first experimental work directed to the study of the relationship between the cost and effectiveness of decontamination procedures was that carried out at Camp Stoneman in 1956.[4] However, it was not until after the second series of tests at Camp Stoneman in 1958[5,6,7] that the present form of the decontamination efficiency concept was recognized. The explicit form of the concept, in general, is an expression of the relationship between the decontamination effectiveness and applied effort, or work-rate, over a period of time. The two basic ideas underlying the concept are that (1) the amount of fallout removed (i.e., the effectiveness) per unit of additional applied effort (in any method) decreases as the applied effort increases, and (2) the application of an infinite, or very large, amount of work will not reduce the residual, or remaining, contamination below a given value without removing the surface of the contaminated material.

9.2 Decontamination Effectiveness and Applied Effort Relationships

9.2.1 Effectiveness Parameters

The basic definition of effectiveness of a decontamination method as a radiological countermeasure is related to the reduction in exposure dose that would result from the removal of fallout particles. For the case of fallout from land detonations where all the radioactive material is carried by particles, the reduction in exposure dose will be practically the same as the reduction in the ionization rate corrected to a given time. Thus the basic measure of effectiveness for this type of fallout is F_r, defined by $R_r(t)/I_r(t)$ where $R_r(t)$ and $I_r(t)$ are the true air ionization rates.

However, decontamination methods remove and transport particles without regard to the specific activity of the particles. Hence the measure of the operational effectiveness of a method is actually R_m/y, in mass units. This ratio is the same as $R_r(t)/I_r(t)$ when the mass contour ratio, $M_r(1)$, is the same for the remaining particles as it is for all the particles originally deposited on the surface. Since the variation of $M_r(1)$ with particle size is not determinable from decontamination experiments with fallout simulants, the ratio R_m/y is most commonly used as the measure of effectiveness. To express the effectiveness of a particular decontamination method, it suffices to state R_m as a function of y.

The major independent parameter that defines the efficiency of a method is the effort, or rate of effort, expended in carrying out the decontamination procedure. In most cases it is convenient to define the effort itself in units of time since the time required to decontaminate a given area is always related to the effort expended. The most common effort-units are expressed in terms of the time required per man, or per unit of equipment, to decontaminate a unit area. Obviously, the rate of movement, or speed and rate of coverage of area with a procedure or with a piece of equipment is involved in this definition.

The residual mass of fallout particles on a surface area not removed by a method, even after the expenditure of a large (infinite) effort, are described by interactions discussed in Chapter 7. For many of the available decontamination methods this residual level is given by

$$M^* = R_M(1 - e^{-k_f y}) \tag{9.1}$$

where M^* is used instead of R_m.

The other functional dependence of M* on the initial level, as found for high pressure water spraying, is given by

$$M^* = R_o y^n \qquad y \leq y_s \tag{9.2}$$

and

$$M^* = R_M \qquad y > y_s \tag{9.3}$$

where R_o and n are constants, and y_s is a surface saturation level above which M* is more or less constant. The parameters k_f and n depend on the surface-method combination and are termed spreading, or smearing, coefficients.

In discussing the efficiency of various decontamination methods it is convenient to divide the methods into two general classes: (1) pick-up methods and (2) pile-up methods. The pick-up methods are those that remove and collect the fallout material in one operation by use of such equipment as motorized sweepers, motorized scrapers, and vacuum cleaners. The pile-up methods are the ones that push the fallout particles from one area to another and, in doing so, increase the surface density of particles along the path of travel. Firehosing, motorized water flushing, and motorized grading or bulldozing are pile-up methods.

The alternate classification of methods, which is much the same, is into "dry" and "wet" methods. It is clear, even from the descriptive terms, that the pick-up methods should have higher efficiencies since they do not increase the surface density of the particles as they proceed over an area.

9.2.2 Efficiency Functions for Pick-Up Methods

On a large scale, a decontamination procedure is carried out by applying a method to a street, or a roof, or a land area once, or twice, or more times in a series of passes or cycles over the area. For each such cycle, the efficiency coefficient of the method for removing the fallout from the surface may be defined as

$$\mathcal{E}_n = \frac{M_{n-1} - M_n}{M_{n-1}} \tag{9.4}$$

where n is the number of the cycle, M_{n-1} is the deposit level of the fallout at the start of the cycle and M_n is the deposit level after the nth cycle.

Because n is just a number and many variations of speed in making the cycle are possible, a more useful definition of the efficiency coefficient is obtained when the single cycle efficiency coefficient is converted to a differential efficiency coefficient and n is transformed to effort units. Thus the differential coefficient, from Eq. 9.4, is

$$\delta\mathcal{E}_n = \frac{-dM/M}{dn} \tag{9.5}$$

The effort, E, in man-hours per unit area, is related to the number of cycles by

$$E = \frac{n\tau}{A_o} \tag{9.6}$$

where τ is the number of man-hours per cycle, and A_o is the area over which the pass is made. The total time spent on the area is $n\tau$ divided by the number of people in the decontamination crew. For a piece of equipment-hours per cycle; then $n\tau$ is the total time spent decontaminating the area.

For a method covering a width, w, at a forward speed, v, the time in man-hours for a crew of N men to make 1 cycle or pass over the area, A_o, is

$$\tau = NA_o/wv \tag{9.7}$$

If dn in Eq. 9.5 is replaced with dE and $\delta\mathcal{E}_n$ is replaced with the constant, K, on the assumption that the efficiency coefficient is independent of both M and E, then Eq. 9.5 is

$$-dM/M = KdE \tag{9.8}$$

If no lower limit is placed on the mass level remaining at large values of E in Eq. 9.8, integration from M = y at E = 0 gives

$$M = ye^{-KE} \tag{9.9}$$

or

$$F = e^{-KE} \tag{9.10}$$

This relationship between F and E was derived by Hong Lee et al[7] for the efficiency of certain land-area surface removal procedures where the soil surface layer has ideal properties for uniform removal.

Land-area surface removal equipment, such as the motorized scraper or grader, decontaminates by removing the fallout particles along with a thin layer of the surface. These methods, used on an ideal smooth soil, might be expected to remove all the fallout particles in a single pass over an area; however, even with the most ideal soil, some of the material is spilled (or missed) over or under the cutting blade or at its edges. In addition, the surface of real terrain contains gross depressions and cracks in which fallout particles lodge; these fallout particles will not be removed if the surface on which they lie is below the surface layer removed.

In the land-area surface removal procedure, each succeeding cut made by the equipment forms a new surface. The ability of the equipment to make a clean cut in removing an additional layer of soil depends on the cohesiveness of the layer being picked up. Since spills can occur under or over the top of the cutting blade, or off its end, it would seem that, when the cohesiveness of the soil improves with each successive surface removal, the spillage should decrease; also, the fraction of fallout removed per pass should increase. However, if the deeper soil is less favorable for removal (because it contains rocks, etc.), and ability of the equipment to make a clean cut decreases, the fraction removed per pass should also decrease.

For an ideal uniform soil, the fraction of the fallout particles removed per pass should remain essentially constant. By definition, the fraction of the fallout remaining after the nth cycle , for all three cases, is

$$F_n = M_n / y \tag{9.11}$$

where

$$\frac{M_n}{y} = \frac{M_1}{y} \quad \frac{M_2}{M_1} \quad \frac{M_3}{M_2} \cdots \frac{M_n}{M_{n-1}} \tag{9.12}$$

and where each of the single cycle ratios (ratio of the fallout mass remaining after the cycle to that on the area at the start of the cycle) may have any value from 0 to 1.

In the case where the condition of the soil for removal does improve with depth, the values of the successive ratios will decrease. If each successive layer is more difficult to remove, the values of the successive ratios will increase. In the case of the ideal soil, they should be constant; in this case

$$F_n = a^n \tag{9.13}$$

or

$$F_n = e^{-k'/n} \tag{9.14}$$

where k' is equal to $\ell n\ y/M$. And since n is proportional to E, Eqs. 9.10 and 9.14 are the same.

In the decontamination of fallout from paved areas, roofs, and painted surfaces a lower limit to the mass of removable particles usually occurs; for this case, the non-removable mass is subtracted from consideration in Eq. 9.8 by replacing M with M-M*. Integration then gives

$$M = M^* + (y - M^*)\, e^{-KE} \tag{9.15}$$

In both Eqs. 9.10 and 9.15, the value of K depends on the method-surface combination.

9.2.3 Efficiency Functions for Pile-Up Methods

The methods considered under this category are only the wet decontamination methods, firehosing and motorized flushing; both utilize high-pressure spray nozzles. Since gravity is the main force in holding the larger particles to surfaces, the action force of the water stream as it impinges on a contaminated surface accelerates the particles from rest positions. If the volume of the water flow over a surface area is large enough and if the surface drainage is good, the bulk water will also transport the particles to new rest positions downstream or into a nearby disposal area.

In most cases, the major factor in the removal of the particles from a contaminated surface is the initial acceleration they receive from the water stream; this acceleration causes each particle to travel with the water stream to some distance away. This process is repeated, as the nozzle and stream is moved forward, when the stream again reaches the point where the particle landed. A detailed description of this process, with respect to particle removal efficiency, is a rather complicated one; it has not yet been satisfactorily resolved. However, approximate empirical functions have been derived from available decontamination data which represent the experimental results almost within the accuracy limits of the original data.

Several important operating parameters in the use of water sprays for removing fallout particles have been identified; many of them have been studied, chiefly by W.L. Owen.[6] These parameters include: (1) the energy

of high velocity streams, (2) the stream pattern, (3) the operating rate, (4) the design of the equipment, and (5) the procedural application of the method. Some of these parameters are critical in determining the decontamination effectiveness achieved for a given amount of expended effort.

In general, firehosing, or even motorized flushing is not ideally suitable to multiple pass or cyclic coverage of contaminated areas. In the usual case, slight adjustments in the operating rate or of one of the other parameters increase the amount of fallout removed more than repeated passes. After the surfaces are wetted and then dried, the remaining particles become much more difficult to remove in the subsequent passes.

The energy of fluid streams striking a surface is given by

$$W = Pt/A \tag{9.16}$$

where P is the kinetic power of the stream, t is the time during which the stream is applied and A is the area covered. Thus more energy is applied when t is large and A is small. The area covered by the stream can be made small by either reducing the radius of the circular stream pattern or by using a nozzle that gives a thin flat jet.

The kinetic power of a nozzled water jet is

$$P = K_1 p Q \tag{9.17}$$

in which k_1 is a constant near the value 1.0, p is the nozzle pressure, and Q is the water flow rate through the nozzle. The value of Q is proportional to the nozzle tip area and to $p^{1/2}$. Thus the energy applied to the unit area increases as $p^{3/2}$ and with the nozzle tip area. The operating rate for applying the energy, W, to the surface is A/t which, in terms of nozzle size and nozzle pressure, is

$$A/t = k_2 a p^{3/2} / W \tag{9.18}$$

If it is assumed that $\mathcal{E}W$ is the kinetic energy required to remove the mass y-M from the area A, then the operating rate required to do this is

$$A/t = \frac{\mathcal{E} k_2 a p^{3/2}}{y - M} \tag{9.19}$$

Experimental data based on visual determinations of the removal of particles[6] indicate that the nozzle pressure dependence of Eq. 9.19 is approached by motorized flushing nozzles which produce a flat thin spray jet;

and, for firehosing nozzles, the dependence is approximately $p^{1/2}$. This suggests that, with firehosing nozzles, the fraction of the energy utilized in removing the particles at a given rate changes with the nozzle pressure. More of the energy would be wasted in a circular spray pattern since only the front edge of the spray pattern removes or accelerates the particles and the remainder of the kinetic energy is expended on cleaned areas. The form of Eq. 9.19 does suggest, however, that an optimum operating rate exists for achieving a given remaining level of contamination; also, if the rate is too rapid the cleaning will be less effective than desired; or, if the rate is too slow, water will be wasted.

The fraction of the mass of fallout particles remaining, from Eq. 9.19, is

$$F = 1 - \frac{\varepsilon k_2 a p^{3/2} E}{N y} \tag{9.20}$$

where E is Nt/A and N is the number of men in the crew. Although Eq. 9.20 indicates the general trend of F with the various important operational parameters, the dependence of the average value of F on these parameters in the decontamination of a large area is more complicated because the effective value of y increases with distance from the starting point of the decontamination; this increase y would, in turn, result in a change in the value of the factor, ε. Since the details of these interrelationships among the operational parameters, for the decontamination of large areas, have not yet been solved either theoretically or experimentally, the efficiency function assumed here for empirical fit to the data is

$$\frac{-dM/(M - M^*)}{dE} = K(E) \tag{9.21}$$

where the apparent efficiency coefficient, K(E) decreases with the effort expended, in a manner described by

$$K(E) = K_o E^{-n} \tag{9.22}$$

Data, from experiments on both firehosing and motorized flushing on areas about 150 feet long and 20 feet wide generally give values of n between 0.6 and 0.7[6]; thus, taking the value of n as being 2/3, integration of Eq. 9.21 results in

$$M = M^* + (y - M^*) \exp(-3K_o E^{1/3}) \tag{9.23}$$

Because of experimental difficulties of maintaining uniform rates with human firehosing crews and of selecting appropriate overlap distances for the adjacent passes of the motorized flusher, the data are somewhat scattered and therefore cannot be used to make a selection between Eqs. 9.1 and 9.2 for the dependence of M^* on y in a precise way.

CHAPTER 9 REFERENCES

1. The Radiological Recovery of Fixed Military Installations, NAVDOCKS TP-PL-13 (1958)

2. Strope, W.E., Radiological Defense Measures as a Countermeasure System, USNRDL-TR-74 (1956)

3. Laurino, R.K., Effectiveness Specifications For Radiological Defense Countermeasures. USNRDL-TR-47 (1955)

4. Sartor, J.D., H.B. Curtis, et al, Cost and Effectiveness of Decontamination Procedures for Land Targets, USNRDL-TR-196 (1957)

5. Owen, W.L., J.D. Sartor, and W.H. Van Horn, Stoneman II Test of Reclamation Performance. Vol. II. Performance Characteristics of Wet Decontamination Procedures, USNRDL-TR-335 (1960)

6. Lee, H., J.D. Sartor and W.H. Van Horn, Stoneman II Test of Reclamation Performance. Vol. III. Performance Characteristics of Dry Decontamination Procedure. USNRDL-TR-336 (1959)

7. Lee, H., J.D. Sartor and W.H. Van Horn, Stoneman II Test of Reclamation Performance. Vol. IV. Performance Characteristics of Land Reclamation Procedures, USNRDL-TR-337 (1959)

Chapter 10

DECONTAMINATION EFFICIENCY FOR REMOVAL OF LAND DETONATION FALLOUT FROM SURFACES

10.1 Background and History

10.1.1 Methods For Paved Areas and Building Surfaces

The first sets of experiments on the decontamination of particles from paved areas and roofing surfaces were reported in 1948 by F.R. Holden and coworkers[1] and by R.A. Laughlin and coworkers.[2] In the first set of experiments, both a motorized street sweeper and a standard firehose were used to remove large and small iron particles from road surfaces. In that experiment, the street sweeper removed the larger particles better than it did the smaller ones, and the firehose removed more of both sizes of particles than the street sweeper did. In the second set of experiments radiotantalum metal particles in three different size ranges were used; in these experiments macadam and concrete surfaces were decontaminated by hand sweeping. The results were similar to those of the previous experiment in that the removal of the larger particles was more complete and the firehosing method gave the lowest remaining levels.

In the first set of experiments, called Operation Streetsweep,[1] decontamination efficiency data were obtained on the removal of the magnetic particles from both macadam and concrete road surfaces. The magnetic particles were iron filings with a median diameter of 700 microns and magnaflux (iron oxide) powder having a median diameter of 12 microns. A weighed amount of the particles was spread evenly over a previously cleaned 8 feet by 10 feet area of the road surface and then the area was swept or firehosed once or twice. The final remaining particles were then completely removed by running a magnet truck slowly over the area; these remaining particles were weighed. The data from the experiments are summarized in Table 10.1.

Where at least 2 passes were made, a correlation of the data of Table 10.1 can be made by use of Eq. 9.15. The KE in that equation is first replaced by $K_n n$, where n is the number of passes made over the area. If R_1 is designated to represent R_m for the first pass and R_2 to represent R_m for the second pass, then M* (of Eq. 9.15) may be calculated from

Table 10.1

SUMMARY OF DECONTAMINATION DATA FROM OPERATION STREETSWEEP

Method	Surface	y (gm/ft^2)	R_m (gm/ft^2)	d_m (microns)	Pass No.	F_n
Sweeper	Macadam	85	4.5	700	1	0.053
Sweeper	Macadam	(4.5)[a]	2.2	700	2	0.49
Sweeper	Macadam	57	9.6	12	1	0.168
Sweeper	Macadam	(9.6)[a]	4.8	12	2	0.50
Sweeper	Macadam	28	5.0	12	1	0.178
Sweeper	Macadam	5.7	1.34	12	1	0.235
Sweeper	Concrete	85	1.3	700	1	0.0153
Sweeper	Concrete	(1.3)[a]	0.45	700	2	0.346
Sweeper	Concrete	57	2.3	12	1	0.0403
Sweeper	Concrete	(2.3)[a]	0.8	12	2	0.348
Firehosing	Macadam	85	0.68	700	1	0.008
Firehosing	Macadam	57	0.006	12	1	0.0001
Firehosing	Concrete	85	0.06	700	1	0.0008
Firehosing	Concrete	57	~0.001	12	1	Negligible

a. Same as R_M from the previous pass; note consistent high values of F_n for second passes.

$$M^* = \frac{yM_2 - M_1^2}{y + M_2 - 2M_1} \tag{10.1}$$

and K_n may be calculated from

$$K_n = 2.303 \log \frac{(y - M^*)}{(M_1 - M^*)} \tag{10.2}$$

The computed values of M* and K_n from the Operation Streetsweep data are given in Table 10.2.

Two-pass experiments were carried out with the sweeper. Only single-pass experiments were carried out for the firehosing method, and no operation rate data were reported.

Table 10.2

COMPUTED VALUES OF M* AND K_n FROM THE DATA OF OPERATION STREETSWEEP

Method	Surface	d_m (microns)	M* (gm/ft^2)	K_n $(pass\ no.)^{-1}$	Pass Numbers
Sweeper	Macadam	700	3.56	3.56	1 and 2
Sweeper	Macadam	12	4.26	2.29	1 and 2
Sweeper	Concrete	700	0.44	4.59	1 and 2
Sweeper	Concrete	12	0.76	3.60	1 and 2

The real effect of the size of the particles on the values of M* and K_n cannot be deduced from the data because the initial deposit levels were different for each particle size. However, the trend in the M* values is to increase as the median diameter of the particles decreases, and the trend in the K_n values is to increase as median diameter of the particles increases.

The indicated trend in M* with particle diameter corresponds to expectations about the variation in decontamination effectiveness with particle size. But the indicated trend in K_n is not expected, according to the

derivations of Eq. 9.15; K_n, the differential efficiency coefficient for picking up the mass of removable particles, in Eq. 9.15 is supposedly a constant. One possible explanation of the observed variation of K_n with particle size for the sweeper is that the smaller particles were not thrown into the hopper as efficiently as the larger particles so that some of the smaller particles, as a suspended dust, settled back to the surface after the sweeper had passed over the area. If this occurred, the decrease in R_m per pass (i.e., K_n) would be less than it was for the larger particles.

The spreading coefficient, k_f, and the constant, R_M, of Eq. 9.1 were evaluated from the decontamination data of Table 10.1 for the sweeper and macadam surface. The values of M* for each test run were also calculated, from Eq. 9.15, using a value of 2.29 for K_n. The numerical values of the three parameters and the experimental y values used in the equations are as follows:

	k_f (ft^2/gm)	R_M(gm/ft^2)	y Values	M* Values
	0.010	9.83	28 and 57	2.40 and 4.26
	0.032	5.08	5.7 and 57	0.85 and 4.26
	0.060	2.80	5.7 and 28	0.85 and 2.40
Median Value	0.027	5.19		

The values of k_f increase, and the values of R_M decrease, as the values of the initial deposit levels increase. These variations may suggest that Eq. 9.1 does not represent the sweeping process very well. However, the same type of variation occurs when the constants of Eq. 9.2 are evaluated from the same data. Recomputation of the M* values from the median values of k_f and R_M gives 0.78, 2.74, and 4.06 gms/ft^2 respectively for the three different experimental y values. These computed values are undoubtedly within the experimental error of the described investigation--i.e., within about 20 percent of the values of M* calculated from Eq. 9.15 using the single derived value of K_n.

At Operation Jangle[3] in 1951, other decontamination methods were tested on paved areas and building surfaces that were placed in the fallout area and contaminated with fallout particles from a low yield underground detonation. Although experimental difficulties during the tests made evaluation of the data somewhat questionable,[4] the tests established that, of the wet methods, high pressure hosing was the most effective; and, of the dry methods tested, high-pressure air jets were most effective and vacuum cleaning was

least effective. No modern type of motorized street sweeper was used in the experiments.

The next set of large-scale experiments in land-type fallout removal from paved and building surfaces was conducted in 1956 at Camp Stoneman.[5] In these experiments the wet methods of firehosing, motorized flushing, and scrubbing were tested; soil particles tagged with radio-lanthanum were used to simulate fallout particles. All the methods tested gave fractions of particle mass remaining of less than 2 percent. Although these experiments proved that a high effectiveness could be achieved in the decontamination of land-type fallout, the decontamination efficiencies were found to be low because of the large expenditures of effort and of water that were used to achieve the high effectiveness values. The results were comparable to the fractions remaining that are associated with the infinite effort remaining level (i.e., M^* or R_{M^*}; see Chapter 8).

In 1958, in the second series of tests at Camp Stoneman,[6,7,8] both dry and wet methods were tested on paved and building surfaces and at various levels of effort. The data and the procedural techniques used in obtaining the data, are discussed in this chapter.

10.1.2 Methods For Land Areas

The first reported experimental work on the removal of fallout from land areas was carried out at Operation Jangle in late 1951.[3] In these experiments fallout from a low yield underground detonation was removed along with desert surface soil by use of motorized scrapers, motorgraders, and bulldozers. The fractions of the ionization rate remaining after single passes of the equipment over the areas, including some contribution of radiation from outside the small test areas, were approximately 10 percent for the motorized scraper, 7 percent for the motorgrader, and 14 percent for the bulldozer.

No further tests were conducted until Operation Plumbbob in 1957.[9,10] In these tests, motorized graders and scrapers were used to determine whether multiple passes or cycles over an area would produce multiple reductions in the fraction of the ionization rate remaining after each cycle. This would be expected if the fractional spillage from each pass is the same; that is, if a single pass left behind 10 percent of the fallout, then after two passes only 1 percent of the original deposit should remain. This result was not obtained because, on the second pass, the cutting blades hit large rocks and much of the second layer of soil--and fallout--was not picked up and removed. The fraction of the ionization rate remaining after the first pass was 16 percent, and, after the second, 11 percent.[9]

Since the characteristics of the soil at the Nevada Test Site are not similar to those of inhabited areas where, if at all, these decontamination methods would be applied, the only useful data from the field tests are those which describe the procedural aspects in doing the work and those which contribute to the basic understanding of the mechanisms of the surface removal process. Because the decontamination effectiveness data from the field test could not be used to evaluate the use of the methods as radiological countermeasures, further tests were carried out at Camp Stoneman in 1958.[3] The procedures and results from these tests are discussed in the following sections of this chapter.

Decontamination methods that actually remove fallout from land areas are all surface-removal methods. The basic idea in the use of these methods is to scrape off as thin a layer of the surface soil as possible that is consistent with the gross roughness of the surface, the ability of the equipment to make the cut, and the over-all effectiveness desired.

10.2 Methods For Paved Areas and Building Surfaces

10.2.1 Firehosing

a. Asphaltic Concrete and Portland Cement Concrete Surfaces

The usual procedure for decontaminating paved areas such as streets, sidewalks, and parking areas by firehosing is as follows: The basic equipment ordinarily used by a firehosing crew includes two standard 1-1/2 inch firehoses jointly fed by a 2-1/2 inch firehose connected to a 500 gallons per minute pump which, in turn, is fed by a nearby hydrant or other water source. A nozzle discharge pressure of 75 to 80 lbs/inch^2 is maintained. In the reported experiments,[6] a standard 1-1/2 inch fire nozzle with a 5/8 inch orifice was used. Calibration data for this and other nozzles are also given by Owen, but this size nozzle gave higher removal rates than most of the nozzles used in the experimental tests.

The firehose crew consists of 5 persons: two nozzle men, two hose men and a fifth man in a vehicle which tows the 2-1/2 inch firehose as the procedure moves along. No special clothing is required for the crews although gloves would help to avoid hand blisters and nonskid heavy shoes or rubbers to keep the feet dry. In most cases the pump is left unattended once it is started up. The arrangement of the crew and the water spray angles (30 to 45 degrees from the plane of the surface) are shown in Figures 10.1 and 10.2. These impingement angles are equivalent to a surface impingement distance of 15 to 20 feet in front of the nozzle men; at the lower impingement angles the removal rate is markedly decreased.

Figure 10.1
FIREHOSING ON A PORTLAND CEMENT CONCRETE PAVEMENT (Arrangement)
THIS VIEW SHOWS THE ARRANGEMENT OF EQUIPMENT AND CREW OF
5 DECONTAMINATING PERSONNEL

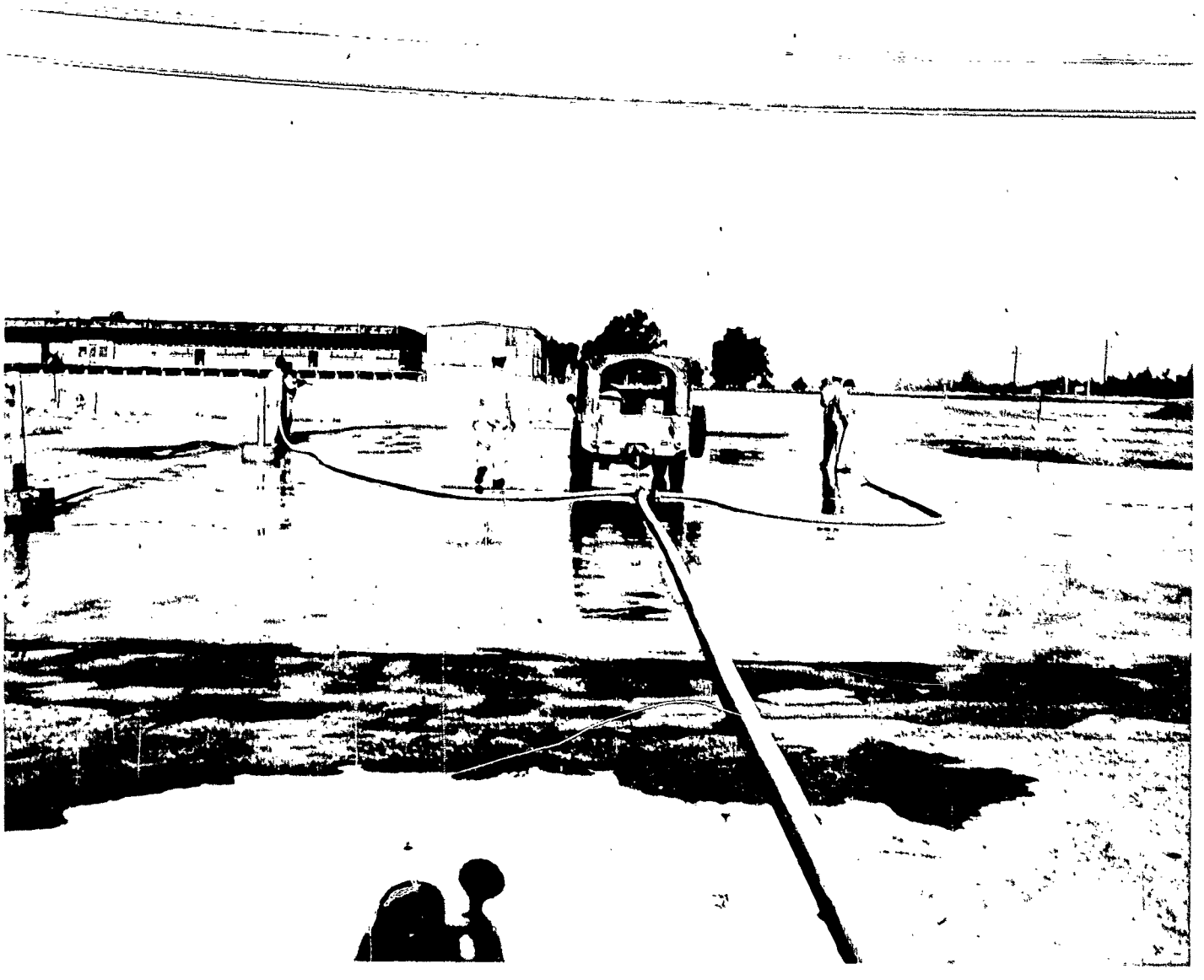


Figure 10.2
FIREHOSING ON A PORTLAND CEMENT CONCRETE PAVEMENT (Angle)
THIS VIEW SHOWS THE ANGLE AT WHICH THE STREAM STRIKES THE SURFACE

On a street, one nozzle-team (1 nozzle man and 1 hose man) cleans on one side of the crown of the street and the other nozzle-team cleans the other half of the street. Each team works from high to low elevations to gain what advantage is possible from the bulk flow of the water.

In city areas, the water and fallout particles would be discharged into the nearest sewage drain or drainage ditch. If these are not available, the runoff can be directed to a shallow pit prepared by a bulldozer, tractor-scraper, or by hand with shovels. After the water has drained into the subsoil the fallout particles can be removed to more remote areas by cleaning out the hole with a skip loader or other loading equipment, and hauled to some pre-selected dumping area. An alternate method would be to dig a fairly deep hole and, after the water has drained into the subsoil, cover the fallout in the bottom of the pit with as much clean soil as necessary for shielding to an acceptable level.

The empirically derived values of the constants of Eq. 9.23 for firehosing asphaltic concrete and Portland cement concrete surfaces are given in Tables 10.3 and 10.4 along with the values of the constants for other methods and surfaces. No guide is presently available for adjusting the values of the constants to account for differences in surface roughness or surface condition when estimating the decontamination efficiency or effectiveness of a method. All that can be stated is that the data were obtained from asphaltic concrete surfaces that had a higher degree of surface roughness than that of a well-traveled asphalt road where the surface is smooth and not cracked. Also, the Portland cement concrete surfaces used in the tests were somewhat smoother than those of the usual broomed concrete surface of many streets and highways.

In the planning and scheduling of decontamination operations, estimates of the rates of application of the method could be made by use of the available data. Then, where the surface condition is known to be poor, the operating rates could be decreased 5 or 10 percent. If the condition of the surface to be decontaminated is very good, the operating rates could be increased by about the same percentage.

As previously mentioned, the data were obtained from areas about 150 feet long; the width of the areas, in most cases, was about that of an ordinary street. In this instance, the fraction of the particles remaining on the surface increased with distance from end of the test area, at which the firehosing started. On a percentage basis, this increase in F_n with distance of travel was not significantly dependent on the initial mass loading of the surface.,

The equation constants of Tables 10.3 and 10.4 however, as derived from the measurements apply to an average fraction or mass level remaining for the whole area. On the assumption that the variation is practically linear with distance, estimates for the remaining level at a given intermediate distance less than 150 feet may be obtained by multiplying the average value of M computed by use of Eq. 9.23 by

$$m_x = 0.68 + 0.0063x \qquad (10.3)$$

where x is the distance in feet from the starting end of the street. Equation 9.23 applies only to firehosing of streets whose surface is fairly level; if the slope of the street gives good water runoff, no correction to M should be applied. Equation 10.3 should not be used to extrapolate the decontamination effectiveness estimates to travel distances greater than about 200 or 250 feet.

b. Roofing Surfaces

Firehosing is the only method generally available for decontaminating roofs that has been tested. Roof washdown decontamination systems on small roof sections[11] and on a larger scale[12] have been tested. But, since such systems are only suitable for special installations, the data are not presented here.

The decontamination of roofs by firehosing can be conducted in two general ways. In direct firehosing, the nozzle and hose men operate from the roof itself; in the lobbing procedure, they operate from the ground. In direct firehosing, the hose-sizes and hook-ups are the same as for firehosing streets but the nozzle may be changed to one having a 3/8x9/16-inch elliptical orifice that produces a flat fan-shaped spray pattern. On the rougher roof surfaces, higher nozzle pressures than those used in decontaminating the paved areas were used in obtaining the data: 120 psi for composition shingle roofs, and 150 psi for tar and gravel roofs. In the latter case, the gravel is removed along with the fallout particles in the process of decontamination.

The firehosing crew for direct firehosing of roofs has 6 members: 2 nozzle men, 2 hose men, and 2 men to help move the hoses on the ground and on the building roof. In a decontamination operation, the last 2 men might be placing hoses on a nearby structure while the other four are firehosing. On small buildings such as houses, only one nozzle team may be used on one roof; so that two adjacent roofs are cleaned simultaneously.

On sloped roofs the firehosing is started at one end of the roof peak and proceeds along the peak with the water stream moving down toward the eaves. On flatter, large-size, tar and gravel roofs, each nozzle team works from one end of the roof center-line towards the roof edge in each of a series of passes in moving down the length of the roof. On each pass or sweep from the center-line, the gravel near the eaves is removed first to minimize windrowing; otherwise windrowed gravel would block the runoff water. Each nozzle team takes half of the roof from the centerline.

If the tar and gravel roof has a parapet more than 2 or 3 inches high around the eaves, one shovel man per nozzle should be supplied to shovel the gravel over the parapet. On other roof surfaces having high parapets, the number of nozzles used, the water flow-rates, and direction of the water stream should be determined from the capacity of the drains and their locations on the roof. Debris that might plug the drains should be removed by hand or by use of rakes and shovels; one extra man per roof may be needed for this work.

On large, tall buildings more men would be required for each firehosing crew to pull hoses to the roof. Standard fire-fighting equipment (trucks, ladders, etc.) could be used advantageously to carry out the decontamination. However, no operational tests of the decontamination of larger buildings have as yet been made. The fan-type nozzle and the arrangement of the crew for fire hosing tar and gravel roofs are shown in Figure 10.3.

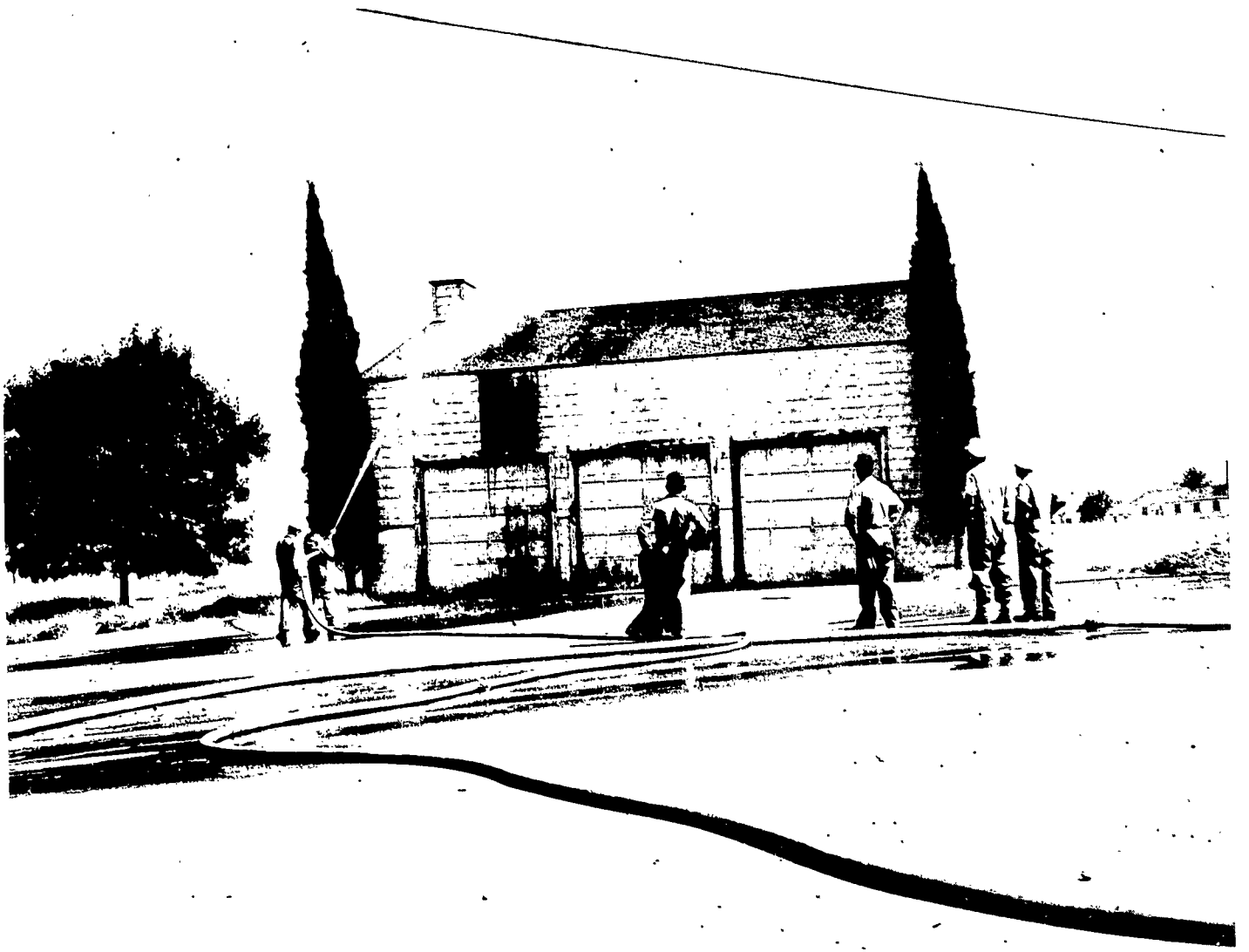
The lobbing procedure is satisfactory only for roofs with sufficient slope for rapid runoff of the water. The procedure; as shown in Figure 10.4, can be carried out with the same crew and equipment that are used for firehosing paved areas. Each nozzle team can work either on the opposite side or on the same side from the building center to the two ends. Since the roof decontamination in the lobbing procedure is done by the runoff water (as in an automatic roof washdown system), the nozzle discharge pressure is reduced to 40 psi. The empirically derived values of the decontamination equation constants for both direct firehosing and the lobbing procedure are given in Tables 10.3 and 10.4.

c. Painted Surfaces

Most painted outdoor surfaces on structures are vertical. Vertical surfaces, however, do not retain a significant fraction of the deposited fallout particles from detonations in soil, according to data[3] from weapons tests. Because the angle between the particles' fall-trajectory and a vertical surface is rather small (especially for the larger fallout particles), the number of particles that strike a unit area of the vertical surface is much less than the

Figure 10.3
FIREHOSING A TAR AND GRAVEL ROOF. THIS VIEW SHOWS ONE OF THE TWO NOZZLE CREWS. THE LOOSE GRAVEL HAS ALREADY BEEN REMOVED FROM THE DECONTAMINATED PORTION OF THE ROOF

Figure 10.4
LOBBING PROCEDURE. THIS SHOWS DECONTAMINATION OF A COMPOSITION SHINGLE ROOF IN WHICH THE STREAM FROM THE FIREHOSE NOZZLE IMPINGES NEAR THE CROWN OF THE ROOF. THE PARTICLES ARE CARRIED BY THE DOWN-FLOWING WATER TO THE GROUND OR, AS IN THIS VIEW, TO THE PAVEMENT FROM WHICH THEY ARE LATER FLUSHED INTO A DITCH AND BURIED UNDER CLEAN EARTH.



number that land on a horizontal surface. Also, of the number of particles that strike a vertical surface, almost all bounce off and land on a lower horizontal surface. Thus, not only smooth painted vertical surfaces, but also the rougher vertical surfaces, retain only a very small fraction of the deposited particles where the fallout levels are high.

The removal of the fallout particles from vertical surfaces, from ledges on vertical surfaces, from window frames, and from other similar minor surfaces could be ignored in a large-scale decontamination operation until after the major more or less horizontal surfaces areas were decontaminated. The contribution of the fallout on these minor surface-types to the gross ionization rates would generally be small compared to the contribution from the fallout not removed in the decontamination of the major collecting surfaces. These minor items could be cleaned by simple manual techniques, such as garden hose flushing and broom brushing, after the major areas have been decontaminated.

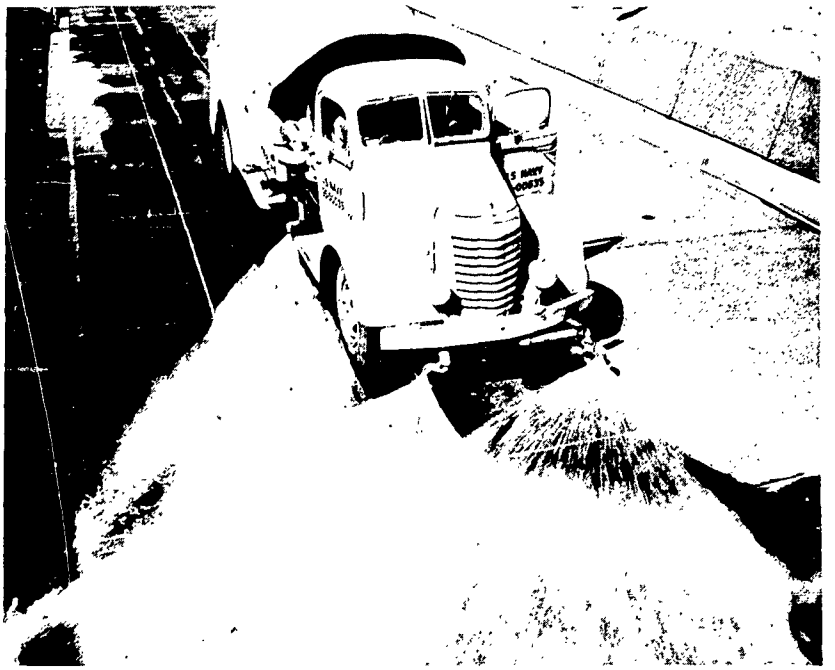
10.2.2 Motorized Flushing of Asphaltic Concrete and Portland Cement Concrete Surface

Motorized flushing can be done with either a conventional motor flusher (CMF) or an improvized motor flusher (IMF). In the reported[6] experimental work a conventional street flusher of 2000 gallon capacity, with a 500-gallons per minute pump and two forward and one side nozzle were used. The nozzle orifices were set at 1/16-inches; the CMF was operated at the maximum available nozzle discharge pressure (55 psi). The two front nozzles were adjusted so that their jets intersected on the pavement in a continuous straight line at an angle of about 60 degrees from the forward direction of travel. The angle the spray made with the surface was set at about 30 degrees. The side nozzle was adjusted to strike the surface adjacent to the point where the spray from the left (or right) front nozzle impinged. The side nozzle moves the particles farther to the side and also keeps the back-flow from the front nozzles away from the flusher. See Figure 10.5.

The flushing procedure usually begins at the side (or corner) of highest elevation in a given area and, ideally, flushes downhill to the front and to the side. However, to conserve time in an operation, the flusher can be used to flush in an uphill direction if the sidewise drainage is satisfactory.

The improvised motorized flusher may consist of any type of tank truck or trailer to which a pump and a home-made nozzle bar can be attached. In the reported experiments the nozzle bar consisted of a standard 2-inch pipe, 8-1/2 feet long, with 14 nozzles placed on centers 6 inches apart. The nozzles gave a flat spray jet and were operated at a nozzle pressure of 85 psi; the spray

Figure 10.5
CONVENTIONAL MOTORIZED FLUSHING ON A PORTLAND CEMENT CONCRETE STREET TEST STRIP. THE SPRAY IMPINGES ON THE SURFACE TO MAKE A STRAIGHT LINE AT ABOUT 60° TO THE LINE OF TRAVEL.



angles for the IMF used in the experiments were the same as for the conventional flusher. The arrangement is shown in Figure 10.6. Forward speeds, with both flushers, varied from about 3 to 16 mph, but for most tests it was about 7 to 8 mph. For calculating the remaining particle mass at various distances of travel from the starting point of decontamination, the multiplying factors to the estimated average remaining masses are

$$m_x = 0.85 + 0.0024x \tag{10.4}$$

for the conventional motorized flusher and

$$m_x = 0.76 + 0.0043x \tag{10.5}$$

for the improvised motorized flusher. The limitations on the use of these equations are the same as for Eq. 10.3 for the firehosing method.

Of the three decontamination equation constants given in Table 10.3, the value of k_f is the most difficult to determine from the observed data. The values of k_f that were derived from the data on the firehosing and motorized flushing experiments are all low compared with the one for the paint samples (see Chapter 8) derived from the data from the simple water washing experiments. The lower k_f values result in a much smaller variation of the smearing term with initial mass loading suggesting that the firehosing and motorized flushing decontamination is more like the high-pressure spraying decontamination described in Chapter 8, and that at the lower mass loadings, Eq. 9.2 would be a better representation of M than Eq. 9.1.

Further studies of these various wet decontamination methods at the lower mass loadings are needed, however, to establish the true nature of the smearing term. The set of constants applicable to Eq. 9.2 are given in Table 10.4. Because of the relative ease of fitting Eq. 9.2 to the experimental data, the values of the constants R_o and n in Table 10.4, along with the values of $3K_o$, give a better representation of the original observed decontamination data than do the set of parameter values given in Table 10.3. In Table 10.4, the values of the constants R_o and n for the painted surfaces were taken from Table 8.2 for the high pressure spray chamber, and R_M was kept at 0.1 gm/sq ft as a value likely to be obtainable with prewetted particles. The values of n for all methods and surfaces listed in Table 10.4 are between about 0.4 and 0.8.

Except for the painted surfaces, the values of the decontamination equation constants were derived from the data in which the simulated fallout consisted of a prefired and sieved Ambrose clay loam soil. This soil mixture contained a fairly large range of particle sizes, with the median size usually about 100 microns in diameter. The soil was tagged with La-140 for measuring

Figure 10.6
IMPROVISED MOTORIZED FLUSHER NOZZLE ARRANGEMENT. THIS STREET FLUSHING ATTACHMENT CAN BE MOUNTED ON ANY TANK TRUCK OR TRAILER THAT HAS, OR CAN CARRY, A BOOSTER PUMP

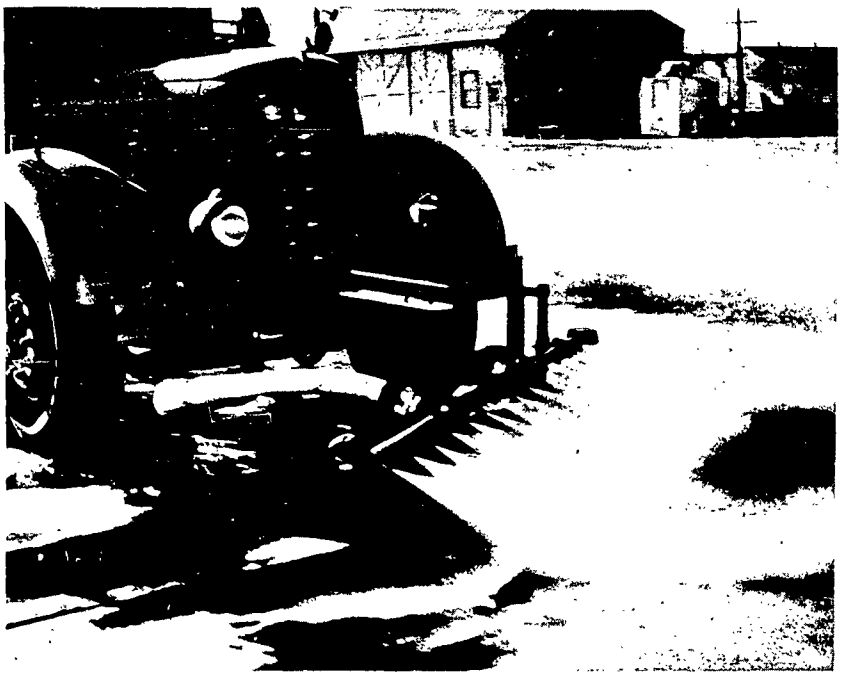


Table 10.3

DERIVED VALUES OF $3K_o$, R_M, AND k_f FOR FIREHOSING AND MOTORIZED FLUSHING OF PARTICLES FROM PAVED AND BUILDING SURFACES

Method	Surface	$3K_o$[a] (sq ft/equip-min)$^{1/3}$	R_M (gm/sq ft)	k_f (sq ft/gm)
Firehosing	Asphalt Pavement	36.9	2.0	8.1×10^{-3}
Firehosing	Concrete Pavement	36.9	1.0	6.4×10^{-3}
Firehosing	Tar and Gravel Roof[b]	23.8	0.80	2.4×10^{-3}
		11.1		
Firehosing	Composition Shingle Roof	21.8	4.0	6.7×10^{-3}
Firehosing	Painted Surfaces	40.0[c]	0.10	1.9×10^{-1}
Lobbing	Composition Shingle Roof	21.8	4.0	6.7×10^{-3}
CMF[d]	Asphalt Pavement	85.5	2.0	8.1×10^{-3}
CMF	Concrete Pavement	85.5	1.0	6.4×10^{-3}
IMF[e]	Asphalt Pavement	85.5	2.0	8.1×10^{-3}
IMF	Concrete Pavement	85.5	1.0	6.4×10^{-3}

a. For firehosing, equip = nozzle

b. Values based on y = mass of gravel (450 gm/sq ft) plus mass of particles; $3K_o$ = 23.8 for 30° fan nozzle; $3K_o$ = 11.1 for 3/8 in. standard (suicide) firehose nozzle

c. Estimated

d. Conventional motorized flusher

e. Improvised motorized flusher

Table 10.4

VALUES OF $3K_o$, R_M, R_o, AND n FOR FIREHOSING AND MOTORIZED FLUSHING OF PARTICLES FROM PAVED AND BUILDING SURFACES

Method	Surface	$3K_o$[a] (sq ft/equip-min)$^{1/3}$	R_M (gm/sq ft)	R_o (gm/sq ft)	n
Firehosing	Asphalt Pavement	36.9	2.0	0.070	0.63
Firehosing	Concrete Pavement	36.9	1.0	0.038	0.53
Firehosing	Tar and Gravel Roof[b]	23.8 11.1	0.80	0.0038	0.74
Firehosing	Composition Shingle Roof	21.8	4.0	0.42	0.38
Firehosing	Painted Surfaces	40.0[c]	0.1	0.013	0.50
Lobbing	Composition Shingle Roof	21.8	4.0	0.42	0.38
CMF[d]	Asphalt Pavement	85.5	2.0	0.024	0.77
CMF	Concrete Pavement	85.5	1.0	0.027	0.63
IMF[e]	Asphalt Pavement	85.5	2.0	0.024	0.77
IMF	Concrete Pavement	85.5	1.0	0.027	0.63

a. For firehosing, equip = nozzle

b. Based on y = mass of gravel (450 gm/sq ft) plus mass of particles; $3K_o$ = 23.8 for 30° fan nozzle; $3K_o$ = 11.1 for 3/8 in. standard (suicide) firehose-nozzle

c. Estimated

d. Conventional Motorized Flusher

e. Improvised Motorized Flusher

the fraction of the soil that remained after decontamination and for determining the initial and residual mass loading of particles on surfaces. Nozzle calibration data, for estimating the water requirements in decontamination, are given in Figure 10.7; the curves were taken from the data of Owen.[6]

Data on the variation of the decontamination equation constants with particle size are not yet available. A great advantage might be gained with a method such as the motorized flusher if, for some particle sizes, conditions of operation were such that speeds of 20 to 30 mph could be used instead of the 7 to 8 mph used in the experiments. Data on the dependence of the equation constants on particle size are also needed to make more accurate conversions of the mass of particles remaining after decontamination to ionization rate intensities through $M_r(1)$.

10.2.3 Motorized Sweeping

The procedures and data presented in this section are taken from the reported work of the Hong Lee and coworkers[7] in which tests were carried out using a Wayne* Model 450 street sweeper, and Tennant** Models 80 and 100 vacuumized sweeper.

The motorized sweepers have a powered rotary broom made of fiber (split hickory, palmyra stalk, african bass, or nylon) or of wire. The ends of these fibers beat or scrape on a surface and throw the particles they hit into a collecting hopper. The vacuumized street sweepers generate very little vacuum; in these sweepers the broom is usually enclosed by a heavy rubber skirt and the external air is pulled in underneath the skirt and is internally passed through a filter. The vacuumizing thus suppresses the dust generated up by the revolving broom. To be effective in decontamination, the sweeper must collect the fallout particles in the hopper; therefore the gutter brooms are removed except during actual cleaning of the gutters.

In the tests, the Wayne 450 sweeper was operated at about 5 mph (7.4 ft/sec), the Tennant Model 80 at 4 mph (6.0 ft/sec), and the Tennant Model 100 at 2.7 mph (3.9 ft/sec). The test area was usually decontaminated by making passes around it until the whole area was swept once (1 cycle); (see Figure 10.8). On large areas, it would be preferable to start in the center, sweep a small area, and then enlarge the clean area by sweeping along its perimeter.

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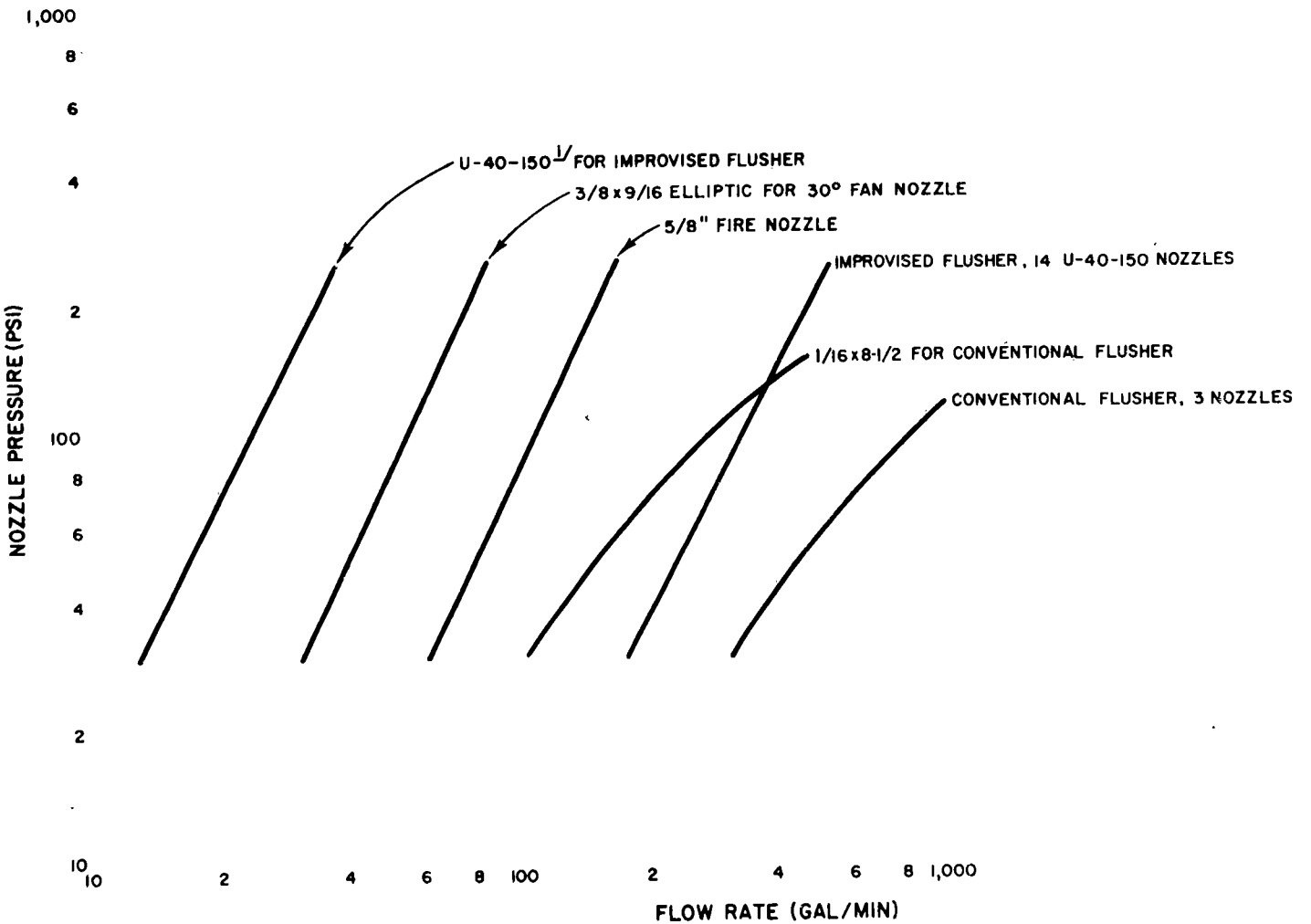
* Wayne Manufacturing Co., Newark, New Jersey

** G.H. Tennant Co., Minneapolis, Minnesota

Figure 10.7
NOZZLE CALIBRATION DATA: FLOW RATES AS A FUNCTION OF NOZZLE PRESSURE

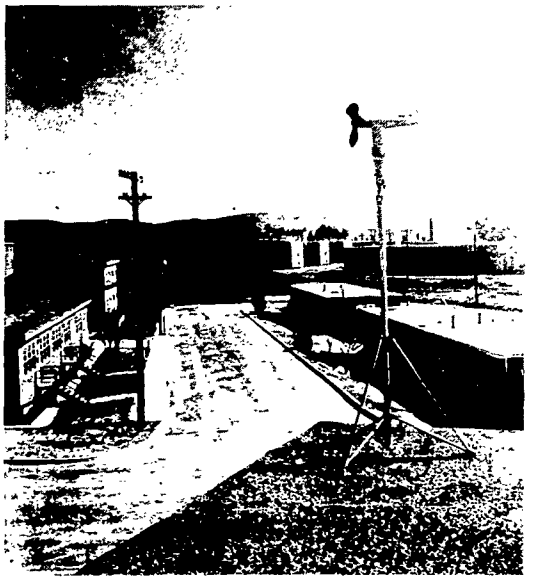


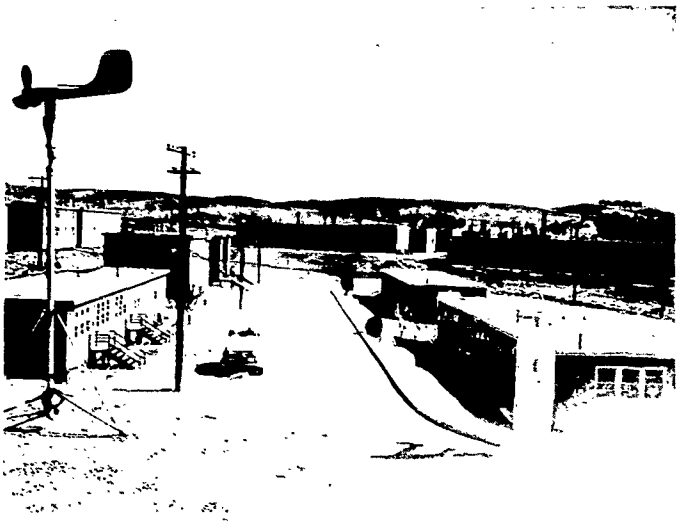
1/ SPRAY SYSTEMS CO. BELWOOD, ILLINOIS

Figure 10.8
MOTORIZED SWEEPING ON ASPHALTIC CEMENT CONCRETE STREETS
(Camp Parks, California)

(a) This view shows a street contaminated with tagged silica (sand) particles. The irregular pattern is due to the action of surface winds and consequent drifting of the particles.

(b) This view shows the sweeper after almost completing one cycle on the street. The gutter broom is operating on this cycle. The board, attached to the front of the sweeper, serves to stop the particles thrown out by the gutter broom so they can be picked up by the large rotary broom





Since sweepers collect fallout particles in a hopper, the radiation rate increases as the hopper fills. Therefore, to keep this source of radiation from giving the operator too large an exposure dose, he must empty the hopper periodically at a nearby disposal area. At that point, the material can be buried, or, it can be loaded on a truck and carried to a remote disposal area.

The values of the constants for Eqs. 9.1 and 9.15, as derived from the data for the three sweepers, are given in Table 10.5. The high value of K for the Wayne 450 sweeper indicates that it was the most efficient of the three sweepers in picking up the fallout at the smaller total effort corresponding to the first or second cycle over the area. However, for larger efforts, the Tennant 100 sweeper was more effective by a factor of 2.

In cases where the values of both K and R_M for one method are larger than they are for another, the two methods can be used serially in decontaminating an area. The method having the larger value of K is used first and the method having the lower value of R_M is used later. In general, the change-over should be determined from the path of least effort to achieve a desired value of M; that is, the path over which -dM/dE is the largest. An approximation equation for determining when to change to the second method is

$$M_x = \frac{K_1 M_1^* - K_2 M_2^*}{K_1 - K_2} \tag{10.6}$$

where the subscripts refer to methods designated by 1 and 2, respectively, and M_x is the remaining mass at which the second method is used.

Table 10.5

VALUES OF K, R_M, AND k_f FOR MOTORIZED SWEEPING

Sweeper	Surface	K (sq.ft/equip-min)	R_M (gm/sq.ft)	k_f (sq.ft/gm)
Wayne 450	Asphalt Pavement	3300	1.95	0.025
Wayne 450	Concrete Pavement	3300	2.10	0.036
Tennant 80	Asphalt Pavement	1200	5.32	0.021
Tennant 100	Asphalt Pavement	2100	1.14	0.012

10.3 Methods For Land Areas

10.3.1 Motorized Scraping

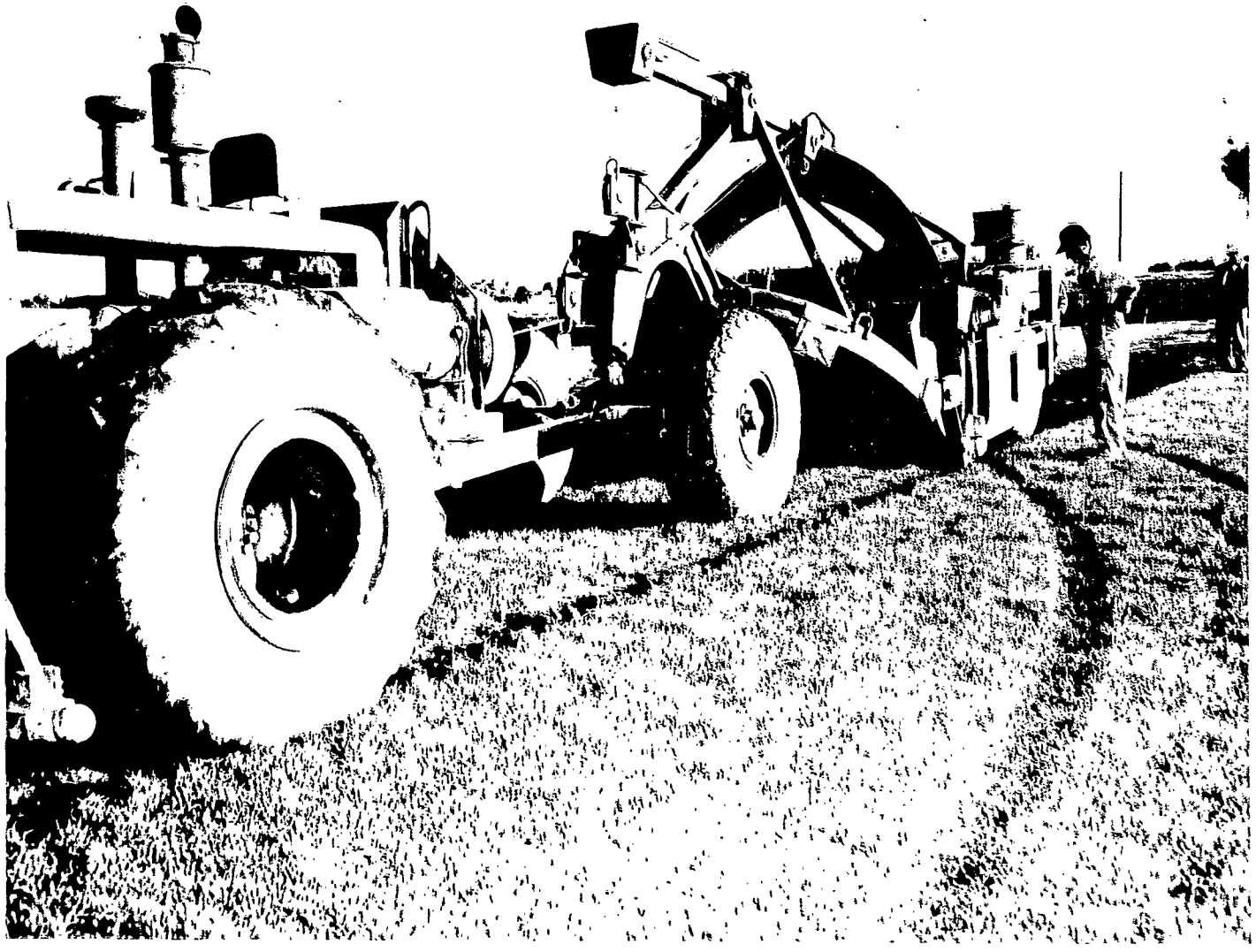
Motorized scrapers are designed to pick up and haul earth; in normal use of this equipment deep cuts are made with the blade to utilize the resistance of the soil mass in filling the hopper. In decontamination, where a very shallow cut is desired, the resistive force that pushes the earth into the hopper is provided only by a thin layer of soil. Thus when the shear strength of the soil layer is low, the layer crumbles and some of it spills around the edge of the blade. When the shear strength of the cut layer is sufficiently large and the layer contains no rocks or other hard solid objects, the cut layer loads into the hopper with negligible spillage. Therefore the decontamination efficiency of motorized scrapers should depend on the nature of the surface soil. It will also depend on the ability of the operator to make uniform cuts, to avoid overfilling the hopper, and to avoid leaving uncut sections of surface soil.

In the reported experiments[8] an 8-cu yd towed-type scraper with a 4-wheel-drive rubber-tired prime mover was used (see Figure 10.9). The basic soil type, Ambrose clay loam, had surface layers of high clay content. Four different surface conditions of this soil were used in the tests; namely: (1) moist soil with grass cover, (2) moist tilled soil, (3) dry tilled soil, and (4) dry native soil with some weed stubble.

Before decontaminating a given plot of land, a nearby dumping or disposal area is selected and prepared for disposal of the stripped contaminated soil. The disposal area is usually a pit, excavated with a scraper or a bulldozer, having sloped ends so that the scraper can be driven into the pit at one end and out the other. The excavated soil is dumped adjacent to the pit and on the side nearest to the area being decontaminated.

The scraping is started at an upwind corner of the area to be decontaminated and proceeds lengthwise down the area taking a 2-inch cut. To minimize spillage, a strip about half the width of the scraper blade is left between the first and second lengthwise strippings or cuts. This strip is picked up on the third cut down the length of the area and on every odd-numbered cut afterward. In a second (or more) pass or cycle, the whole procedure is repeated again starting at the same upwind corner. Along each cut, the loading is stopped before the hopper is completely full and is dumped in the prepared pit. With a 2-inch deep cut the average cut length, for the 8 cu yd scraper, is about 100 feet. Once an operator becomes used to taking the shallow cuts, the procedure utilizes the scraper to within about 80 percent of rated capacity even when the operator pays a good deal of attention to avoid spillage and to making clean smooth cuts.

Figure 10.9
MOTORIZED SCRAPING ON MOIST SOIL, WITH GRASS COVER. THE CUTTING BLADE IS SET TO SCRAPE OFF ABOUT 2 INCHES OF SOIL ALONG WITH THE SOD, AND THE SOIL IS DUMPED INTO A NEARBY HOLE OR PILE. THE EFFECT OF THE SHIELDING BY THE EARTH IN SUCH A PILE IS DISCUSSED IN CHAPTER 12



The values of K derived from the data for Eq. 9.10 are given in Table 10.6. Equation 9.10, rather than Eq. 9.14, was used to evaluate K from the data because in most cases the effort expended in the scraping decreased with successive passes over the area and because the conversion to the time spent in scraping is simplified when the effort is expressed in equip-min/unit area. The tabulated values of K are either single values determined from the data for one pass or averages of the K values determined from the data for two passes over the area. Use of the K values in Eq. 9.10 to estimate the decontamination effectiveness, in general, is for an ideal soil condition and for up to two passes over the area.

10.3.2 Motorized Grading and Scraping

In this combination method, the motorgrader grades off the surface of the soil into windrows and the motorized scraper picks up the windrows and carries the soil to a dumping area. As with the scraper, the motorgrading is started on the upwind side of the area to be decontaminated and the first cut is taken along the length of the area. In grading off a 2-inch surface layer, two cuts can be made with the blade, to produce an 8-foot wide cut, before the windrow is picked up by the scraper.

To avoid moving too much soil as well as to avoid excessive spillage under the blade in low spots in the surface, the blade should be set at angle sufficiently large that the soil runs smoothly off the trailing edge of the blade; also, the pitch of the blade should be set so that the soil does not spill over the top of the blade. Other than these specifications, the use of the grader in decontaminating land areas is the same as its normal use. The divided values of K, in Eq. 9.10, for this method are given in Table 10.6.

10.3.3 Bulldozing

Bulldozing, to remove thin layers of soil and to push the soil away in decontaminating land areas is limited to small areas where the length of the cut is 100 feet or less. If the soil is loose, much of it spills off the end of the blade. The bulldozer should be therefore most useful in removing lawns and shrubs, especially when a front end loader or skip loader is used to pick up and load the spill.

In confined areas, the bulldozer is used to grade off a thin surface layer in the same way as a motorgrader. The scraped spill is then loaded into trucks and carried to a remote area or dumped directly into a nearby waste disposal or holding area. An example of this use is described in Chapter 12.

Table 10.6

IDEALIZED DECONTAMINATION EFFICIENCY COEFFICIENTS FOR LAND AREA METHODS ON A CLAY-TYPE SOIL[a]

Method	K(sq ft/equip-min) Condition of Soil Surface			
	Moist, with Grass Cover	Moist, Tilled	Dry, Tilled	Dry, Hard
Motorized Scraping	1200	880	810	420
Motorized Grading and Scraping	250	300	270	300
Bulldozing	--	--	--	410

a. Ambrose Clay Loam

In an open area, the bulldozer can be used to prepare, in a very short time, small decontaminated protection areas. This is done by first pushing the top layer of contaminated soil out to a distance of 50 to 100 feet in each of four directions. Then, by taking additional cuts as necessary, additional earth is piled up to form a barrier several feet high around the scraped area. At Operation Plumbbob[9] such a barrier was made around an area 100 feet on a side; the shielding effect of the earth barrier was the same as if all the surrounding area had been decontaminated.

The idealized efficiency coefficients for bulldozing along with other soil-removing methods are given in Table 10.6. The method tested of highest efficiency is the motorized scraping of moist soil with grass cover; the method of lowest efficiency is motorgrading the same type of surface soil condition. In the experiments, this surface soil condition actually was sufficiently wet that the grader had difficulty in maintaining traction.

Part of the difference in efficiency between the two methods is due to the factor of 2 for the effort per unit equip-min of the grader-scraper combination. With the motorized scraper, the efficiencies are higher for the tilled and moist conditions where the cohesion of the soil was high. The lower efficiency value for the dry hard soil was due in part to fissures and cracks in the soil surface into which the tagged soil (the simulated fallout) fell. But even discounting the cost of an additional piece of equipment and its operator for the motorgrader-scaper combination, motorized scraping was still the more efficient method in the reported experiments.

The general soil characteristics that would contribute to greater efficiencies in land area decontamination are that the soil should be (1) cohesive, (2) firm but not hard, (3) moist but not wet, (4) smooth and flat, (5) free of rocks, and (6) uniform in composition to at least a depth of 4 to 6 inches. For comparison purposes, the loose dry soil of Nevada gave an efficient coefficient using (Eq. 9.4) of about 0.84 for 1 pass with motorized scraping, but on the second pass the coefficient was only 0.31. With both trained operators and good soil surfaces, efficiency coefficients higher than 0.95 on the first and second passes in motorized scraping should be relatively easy to attain.

Effort-effectiveness data for other decontamination methods, and for shielding by covering with earth, are summarized in Table 10.7. The use of a tractor-scraper is shown in Figure 10.10. Data on agricultural decontamination, not covered here, has been obtained by James and coworkers[13] of the U.S. Department of Agriculture.

The fuel requirements for the types of decontamination equipment used can be quite accurately estimated from: 5 gal/hr consumption rate for gasoline engines (500 gpm booster pump, jeep or pick-up truck, street sweeper, dump trucks, etc.); and 6.5 gal/hr consumption rate for diesel equipment (scrapers, graders, pay-loaders, bulldozers, etc.). When these consumption rates are used to estimate total operating fuel requirements, the gross estimated operating time (working time plus setup time) should also be used to account for a nominal margin of fluctuation in the consumption rates of different engines.

Figure 10.10
TRACTOR SCRAPING OF A LAWN. THE SCRAPER IS WEIGHTED WITH A DRUM OF WATER TO HELP IT MAKE CLEAN CUTS THROUGH THE SOD. THE EXTRA MAN IN THE PICTURE IS KEEPING CLEAR OF THE GROUND A CORD FROM A RECORDER TO A RADIATION DETECTOR CARRIED BY THE TRACTOR OPERATOR. THE RECORD OF THE RADIATION RATE IS USED TO ESTIMATE THE DOSE RATE RECEIVED BY THE OPERATOR IN THE TEST OPERATION

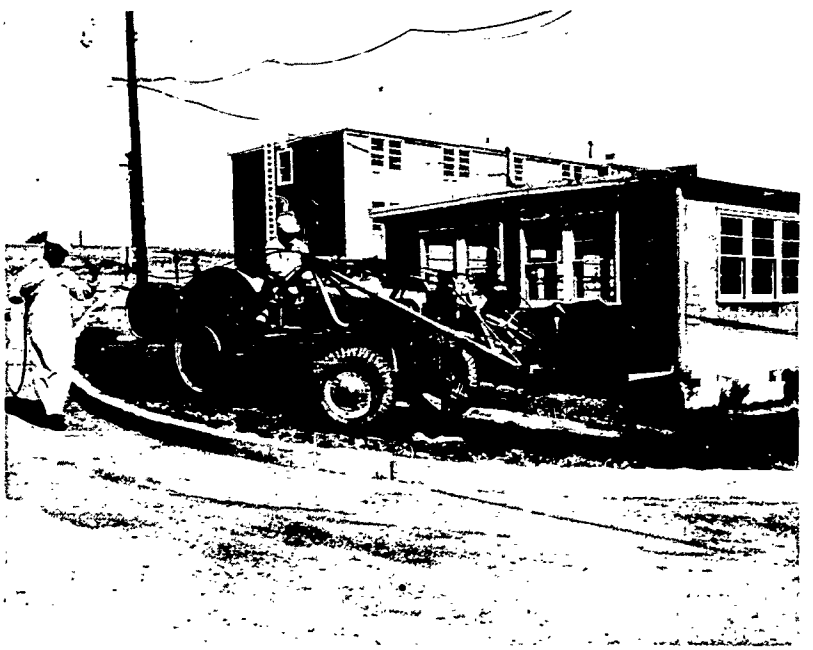


Table 10.7

EFFORT-EFFECTIVENESS DATA FOR MISCELLANEOUS DECONTAMINATION METHODS AND SHIELDING BY COVERING WITH EARTH

Method	Rate[a]	F	Crew Size	Comment
1. Scraping with Wheel Tractor	90	0.1	2	open areas; operator plus man with shovel;
	50	0.15	2	confined areas
2. Scraping with Jeep or Small Truck towing bucket scraper	25	0.07	3	operator plus two "bucket" men
3. Scraping with Shovels and Hauling with Wheel Barrows	15	0.15	4	2 shovel men, 2 wheel barrow men; bare soil;
	20	0.1	4	light soil with some sod;
	10	0.2	4	rocky soil plus shrubs
4. Sod Cutting and Lawn Removal with 18-inch Power Sod Cutter	35	0.02[b]	7	good sod, 1 operator; 5 wheel barrow men; 1 helper (with shovel)
5. Plowing with 4-share Gang Plows	400	0.2	1	continuous plowing;
	250	0.2	1	one-direction plowing
6. Covering with Earth Fill With Motorized Scraper	300	0.15	1	6-inch earth cover;
	150	0.02	1	12-inch earth cover;
	75	0.002	1	18-inch earth cover

a. sq ft/min.
b. Estimated

Note: The efforts for Methods 1, 2 and 3 are for dumping the spoil in a pile at the edge of a small area. Loading the spoil on trucks and hauling it to a disposal area is considered separately. These methods are applicable to decontamination of grounds, or land areas, adjacent to buildings; the assumed depth of soil removed is 1 to 2 inches. With two trucks for direct loading on lawn areas (and short haul distances), the rate for sod cutting would be about twice that given above. In Method 6, the rate is given for very short haul distances; for longer hauls, engineering manuals describing the equipment should be used to estimate the over-all rate; trucks and loaders could also be used in Method 6.

CHAPTER 10 REFERENCES

1. Holden, F. R., R. A. Laughlin, et al, Operation Supersweep, USNRDL-ADZ-42(1948)

2. Laughlin, R. A., J. Howell, et al, Operation Streetsweep, USNRDL-ADX-39(1948)

3. Strope, W. E., et al, Protection and Decontamination of Land Targets and Vehicles Operation Jangle, WT-400 del, (1952)

4. Miller, C. F., Estimated Effectiveness of Common Decontamination Methods For Paved Areas and Building Surfaces, USNRDL-TR-140(1957)

5. Sartor, J. D., H. B. Curtis, et al, Cost and Effectiveness of Decontamination Procedures for Land Targets, USNRDL-TR-196(1957)

6. Owen, W. L., J. D. Sartor, and W. H. Van Horn, Stoneman II Test of Reclamation Performance. Vol. II. Performance Characteristics of Wet Decontamination Procedures, USNRDL-TR-335 (1960)

7. Lee, H., J. D. Sartor, and W. H. Van Horn, Stoneman II Test of Reclamation Performance. Vol. III. Performance Characteristics of Dry Decontamination Procedures, USNRDL-TR-336(1959)

8. Stoneman II Test of Reclamation Performance. Vol. IV. Performance Characteristics of Land Reclamation Procedures, USNRDL-TR-337(1959)

9. Strope, W. E., Evaluation of Countermeasure System Components and Operational Procedures, Operation Plumbbob, WT-1464 (1958)

10. Miller, C. F., Analysis of Radiological Decontamination Data Obtained From Field Tests, USNRDL-TR-321 (1959)

11. Kehrer, W. S., and D. C. Clark, USNRDL-TR-to be published (1961)

12. LaRiviere, P. D., and R. Heiskell, private communication. USNRDL (1961)

13. James, Paul R., and R. G. Menzel, Plant Food Review 5, No. 2, 5(1959)

Chapter 11

BASIC CONCEPTS OF PLANNING RADIOLOGICAL DEFENSE ACTIONS

11.1 The Dose Rate Multiplier

The basic data that describe the radiological hazard from fallout in terms useful for planning radiological defense actions are derived from information on the variation of the air ionization rate with time. Shortly after fallout arrives at a location, the air ionization rate increases rapidly, rises more slowly to a maximum value, and then begins to decrease. After fallout ceases, the ionization rate decreases with time at a rate that depends on both the decay rate and abundance of each radionuclide in the fallout. The integral, or sum, under a decay curve representing the variation of the ionization rate with time, from one time to another, gives the exposure dose during the time interval.

For radiological planning computations it is convenient to separate the ionization rate-time curve into two parts. The first is the portion of the curve between fallout arrival and fallout cessation and the second is the portion over which radioactive decay takes place. The first portion of the curve covers a relatively short period of time during which passive types of countermeasures such as shelters would normally be used. The second, decay portion of the curve, can be used in most of the planning calculations for the active type radiological countermeasures.

To estimate exposure dose for the first portion of the curve requires use of the fallout scaling system for computing the arrival and cessation times and the variation of the ionization rate with time during the period of fallout deposition. To estimate the exposure dose the second portion of the curve requires only the specification of an appropriate decay curve.

A very useful parameter for estimating exposure doses from an assumed decay curve is the dose rate multiplier, defined as

$$DRM = \frac{1}{I(1)} \int_{t\,=\,1\ hr}^{t} I(t)\,dt \qquad (11.1)$$

If a DRM curve is determined as a function of t, the exposure dose, D, for the time interval from t_1 to t_2 after detonation is estimated from

$$D = I(1) \left[DRM(t_2) - DRM(t_1)\right] \tag{11.2}$$

where $DRM(t_2)$ is the value of DRM at t_2 and $DRM(t_1)$ is its value at t_1.

The use of a single DRM in planning calculations assumes that I(t)/I(1) is the same at all points in the fallout area. This assumption is known not to be precisely true. However, the fact that differences in I(t)/I(1) occur does not invalidate the general use of a DRM function; and, unless the times and doses are extremely critical for some operation, the use of a single ionization rate decay (and DRM) curve should not, in general, invalidate the planning estimates obtained, providing a typical or average decay curve is used.

The DRM curve of Figure 11.1 and Table 11.1 was obtained from the decay curve of Figure 11.2; the latter includes the equivalent ionization rate from the decay of about 1 atom of U-239 per fission activated at zero time. The DRM curve flattens to essentially zero slope at 20,000 hours (2.3 years) with a maximum value of about 3.95; this is the infinity dose rate multiplier. For the $t^{-1.2}$ equation, the infinity dose rate multiplier is 5.0. The DRM curve of Figure 11.1 is used in all illustrative computations where the dose rate multiplier is used for estimating either exposure doses or exposure times.

The decay curve of Figure 11.2 was taken from data calculated for a fractionated fission-product mixture from 8-Mev neutron fission of U-238.[1] The curve corresponds fairly closely to the curve of Figure 6.1 (see Chapter 6, Volume I) for fission product condensations up to 60 seconds after detonation, except for the addition of the ionization rate contributions from U-239 (and NP-239).

11.2 The Residual Number

The residual number, RN,[2] is used as a measure of the effectiveness of radiological countermeasures; it is defined as the ratio of the exposure dose that would be received when a countermeasure is used to the exposure that would be dose received without use of the countermeasure. From a measurement point of view, the residual numbers are referred to the air ionization rate 3 feet above the surface of the ground. The residual number also refers to a location, in the sense that a shelter has a residual number, or that the decontamination of a given large area results in a given residual number.

Figure 11.1
DOSE RATE MULTIPLIER CURVES OBTAINED FROM INTEGRATION OF THE DECAY CURVE OF FIGURE 11.2

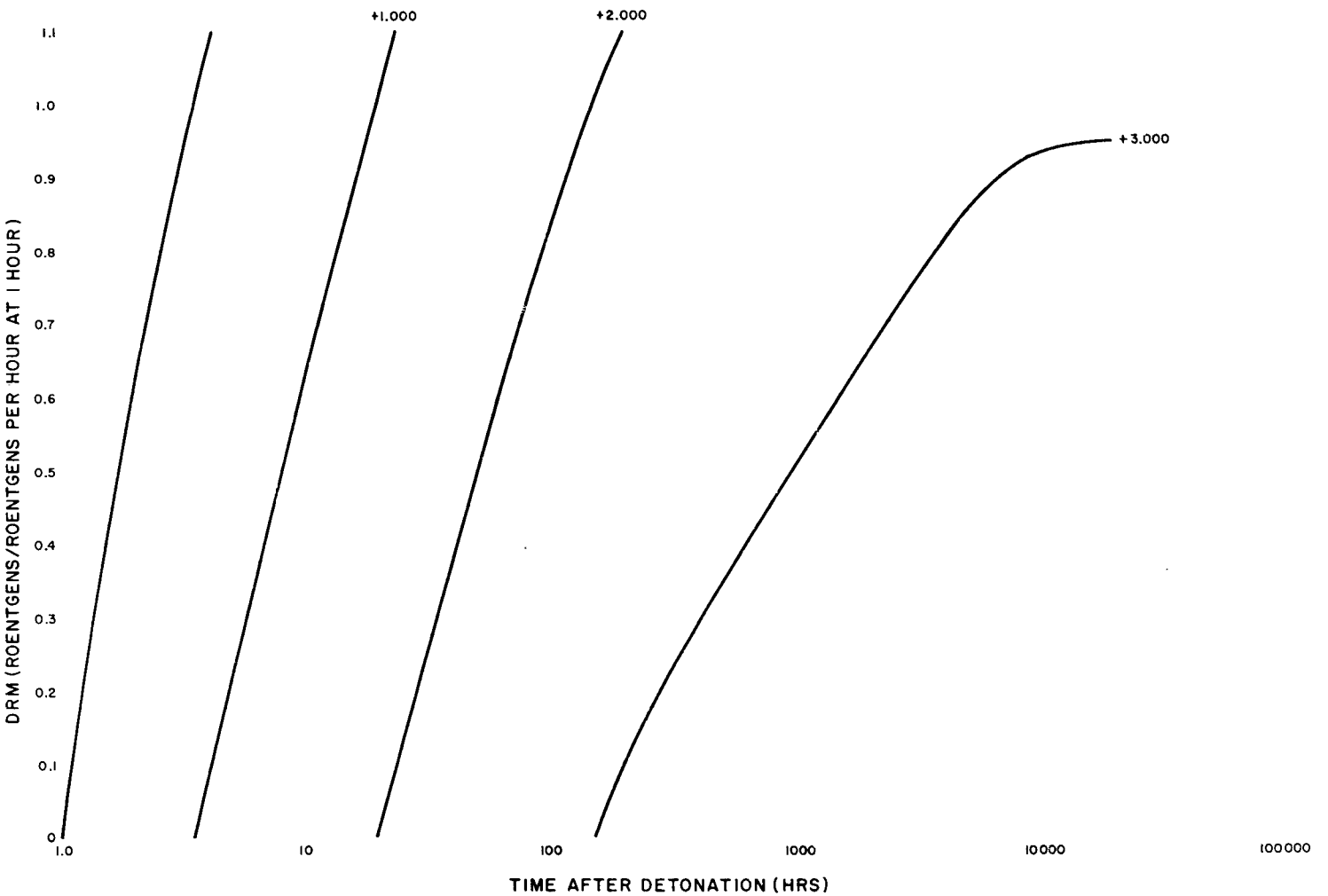


Table 11.1

SUMMARY OF DRM[a] VALUES USED TO CONSTRUCT FIGURE 11.1 FROM INTEGRATION OF THE DECAY CURVE OF FIGURE 11.2

t(hrs)	DRM	t(hrs)	DRM
1.0	-0-	160	3.016
1.2	0.178	180	3.058
1.4	0.320	200	3.094
1.6	0.436	250	3.163
1.8	0.533	300	3.214
2.0	0.614	400	3.286
2.5	0.776	500	3.339
3	0.899	600	3.381
4	1.082	700	3.417
5	1.219	800	3.448
6	1.328	900	3.475
7	1.419	1,000	3.499
8	1.497	1,200	3.540
9	1.565	1,400	3.574
10	1.626	1,600	3.604
12	1.729	1,800	3.630
14	1.815	2,000	3.653
16	1.889	2,500	3.703
18	1.953	3,000	3.744
20	2.009	4,000	3.805
25	2.126	5,000	3.848
30	2.221	6,000	3.876
40	2.369	7,000	3.895
50	2.484	8,000	3.908
60	2.577	9,000	3.923
70	2.653	10,000	3.929
80	2.718	12,000	3.937
90	2.773	14,000	3.940
100	2.821	16,000	3.942
120	2.901	18,000	3.944
140	2.965	20,000	3.945

a. Dose Rate Multiplier

Figure 11.2
COMPUTED IONIZATION RATE DECAY CURVE FOR VERY CLOSE-IN FALLOUT FROM A HIGH-YIELD LAND SURFACE DETONATION BASED ON AN ASSUMED SOIL MELTING TEMPERATURE OF 1400°C

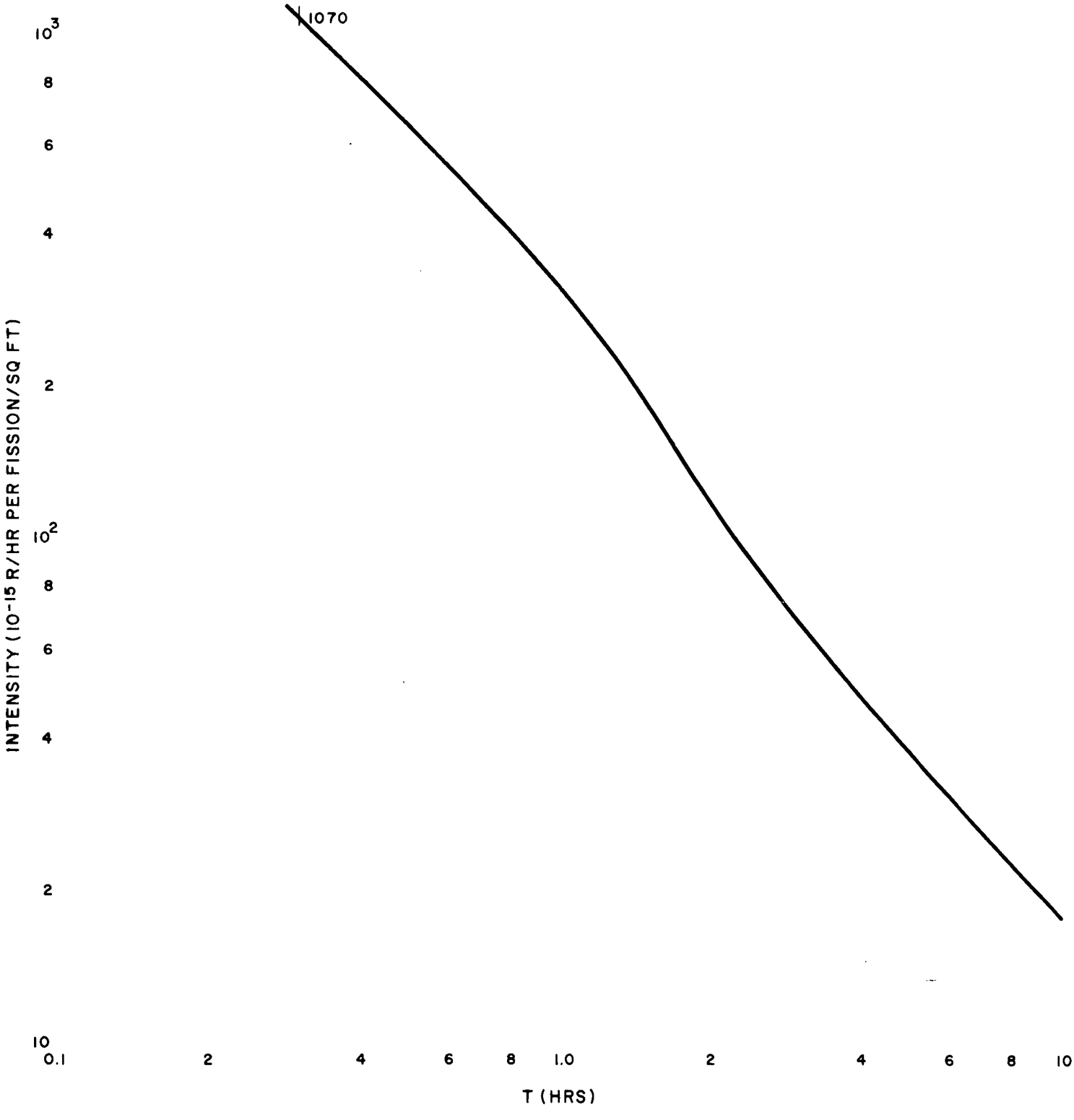


Figure 11.2 (continued)

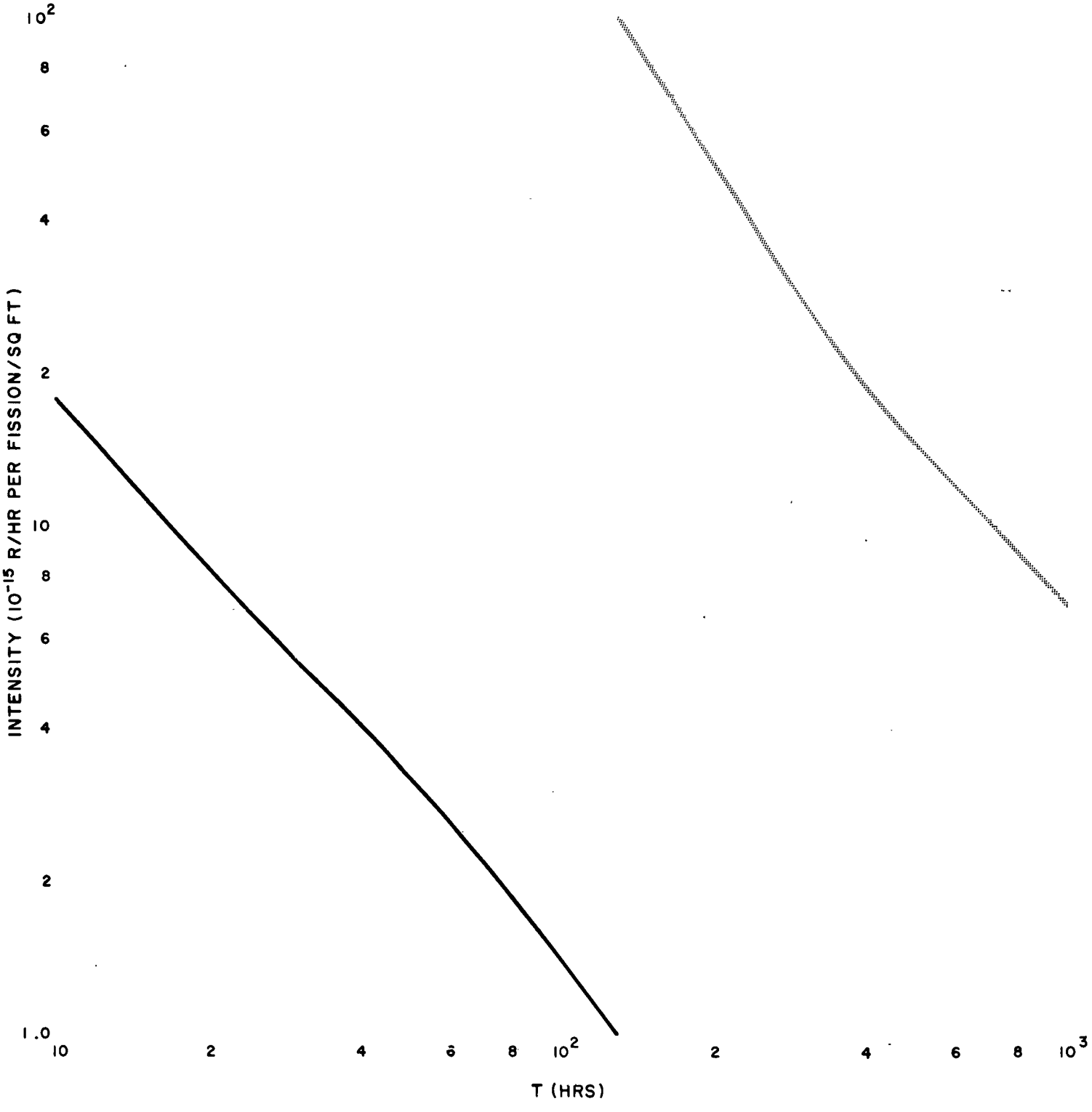
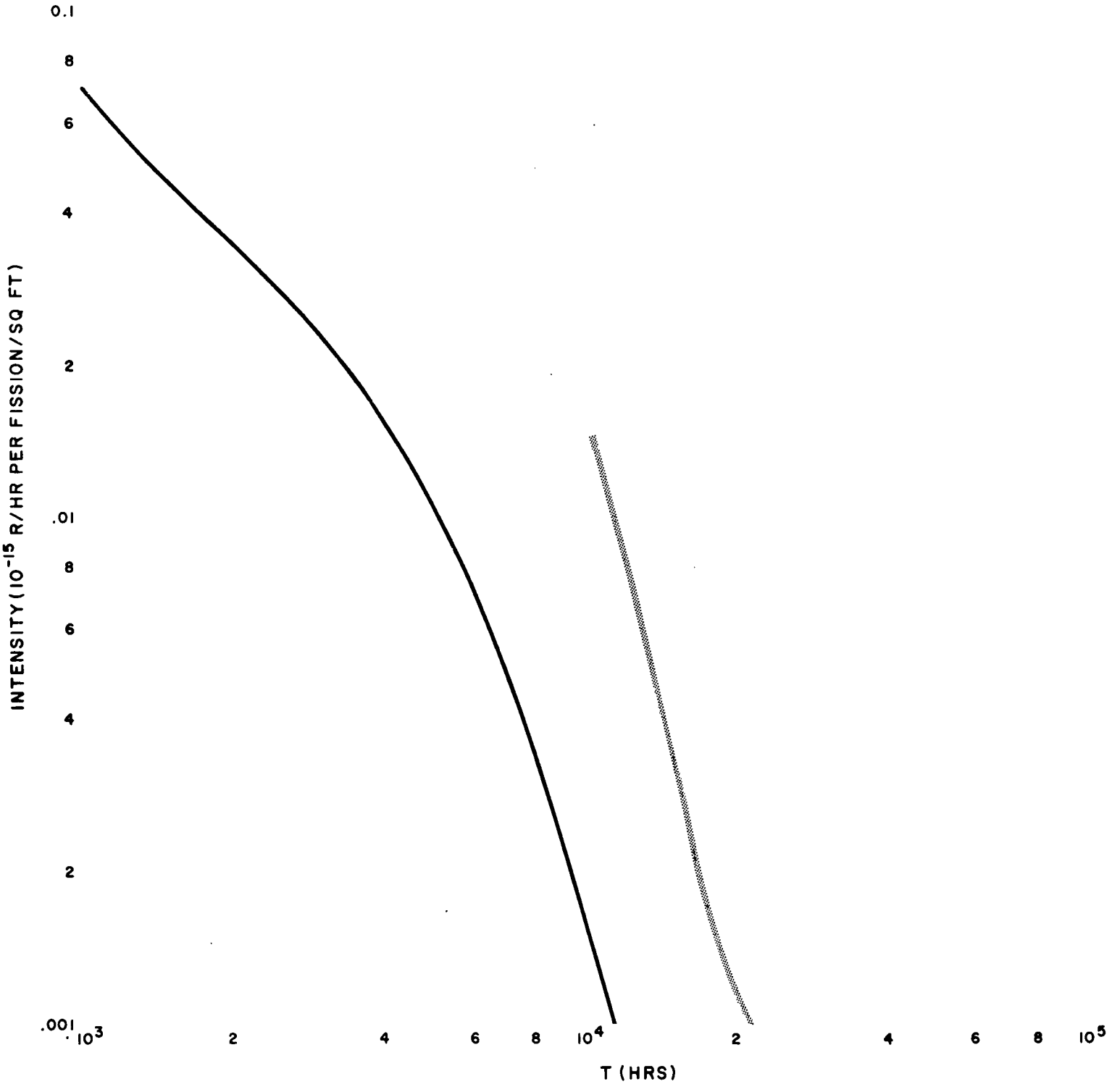


Figure 11.2 (concluded)



The effective residual number of a radiological defense system that includes both shelters for survival and decontamination measures for recovering the use of vital facilities and normal living conditions is derived from the combination of residual numbers for each of the component countermeasures. The three major component residual numbers are: (1) the shelter residual number, RN_1; (2) the decontamination crew residual number, RN_2; and (3) the decontamination residual number, RN_3.

None of the component residual numbers are simple quantities. A single individual shelter will have a range of residual number values; the highest value might apply to a location near a door or vent opening in the shelter while the lowest value may apply to some remote corner of the shelter. But in a practical sense, the most useful value of the residual number for the countermeasure system, or for one of its component parts, is the value that best represents the reduction in exposure dose of people. Thus, for a shelter, the best value of RN_1 is an average value of the RN_1's for the spaces usually occupied.

The value of the decontamination crew residual number, RN_2, depends on the length of time that each member spends working in a contaminated area, and on what work he does. For example, at the start of a decontamination operation, a fire hosing crew would be exposed to 100 percent of the ionization rate from the fallout. But, after cleaning on the area for some period of time, the crew may be exposed only to radiation from the fallout in front of them since the surfaces behind them have been cleaned. The exposure dose of a motorized sweeper operator, on the other hand, would be increased, relative to standing in the open, because of the fallout collected in the hopper of the sweeper.

In any area that contains several different kinds of surfaces for which different decontamination methods must be used, the value of the decontamination residual number, RN_3, depends on the decontamination effectiveness achieved on each of the surfaces, on the size of the area of each surface, and on the distance between each surface area and the location for which the residual number applies.

Normally, the decontamination residual number, RN_3, also includes the shielding effectiveness of surrounding structures and obstructions. For example, most people spend much of a day's time inside structures; thus, in a decontaminated area, their exposure dose would be decreased by both the decontamination and the structures' shielding -- providing the inside of the structure is kept clean of fallout. If all surfaces, outside and inside, gradually became uniformly contaminated with low levels of radioactive material, then the value of RN_3 might approach the same value everywhere.

Many other countermeasures actions could also be assigned separate RN numbers. Some even attempt to include the effects of wind, rain or snow; however, in planning radiological defense action requirements it would be prudent to restrict the planning estimates first to what is required of the over-all countermeasure system without accounting for outside accidental or non-predictable help. The requirements and schedules of the later countermeasure actions can be revised when--and if--such help appears.

11.3 The Allowed or Planning Dose Restriction

The allowed or planning dose restriction is used in planning and scheduling as a mathematical parameter for determining the effectiveness of a radiological countermeasure system or of one of the system's component parts. In other words, the planning dose is a boundary condition for specifying the upper limit of the residual number for each (or all) of several possible types of radiological countermeasures. Mathematically, the restriction may be written as

$$D^{*} \geq RN_1 D_1 + RN_2 D_2 + RN_3 D_3 \qquad (11.3)$$

where the RN's are the same as defined in Section 11.2; D_1 is the outside potential exposure dose during the stay in shelter; D_2 is the outside potential exposure dose during the recovery period; and D_3 is the outside potential exposure dose (i.e., without decontamination) for the time period after radiological recovery is completed.

If RN_1 is sufficiently small, the first term may be neglected and only remaining terms considered. Also, for persons not engaged in recovery operations, RN_2 does not apply, and only the third term needs consideration. On the other hand, if no radiological recovery operations are accomplished, RN_2 and RN_3 are unity, and only RN_1 remains to be determined. The value of D* can be arbitrarily selected, in a mathematical sense, for determining a set of solutions for the various RN's. But even then each value has some relationship to biological effects.

The real significance of Eq. 11.3 is that, through it, the performance requirements and cost of the countermeasures can be specified in terms of biological consequences. Equation 11.3 can be solved only when sufficient data are available for estimating the six parameters. Equation 11.3 can also be solved by selecting appropriate values of D* for each of the respective terms on the right side of the equation. The use of several alternate definitions of D* is illustrated in the following sections.

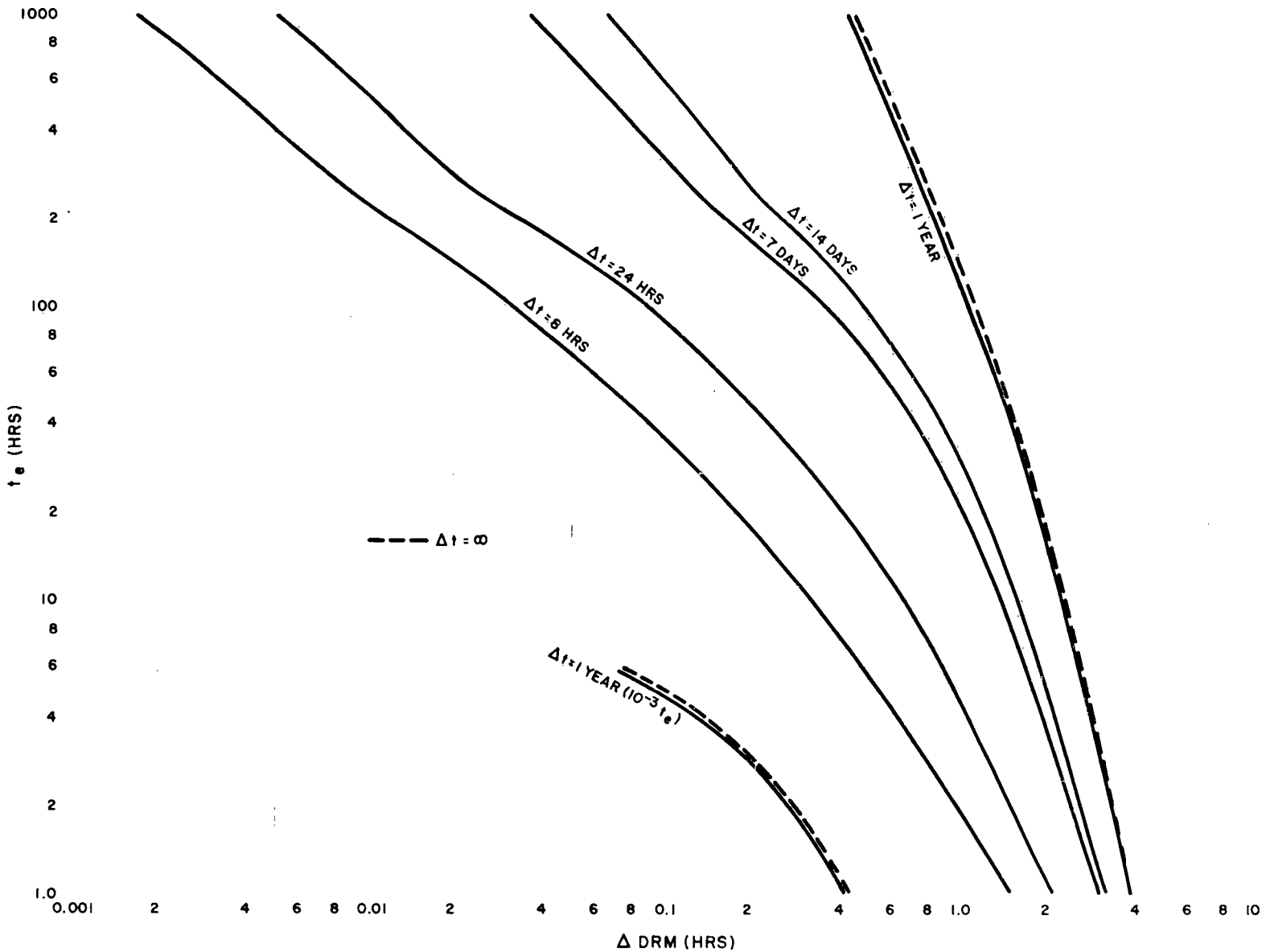
11.4 The Minimum Shelter Stay Time

To estimate shelter stay times for various levels of fallout, without considering radiological recovery countermeasures (i.e., RN_2 and RN_3 are equal to one), it is convenient to use an alternate definition of D*. The set of D* values selected for discussing the dependence of shelter stay time on other parameters is: 30r in 1 day and 1000r in 1 year. In Chapter 7, the 30r in 1 day planning dose led to the requirement of an RN_1 value of 0.0083 (1/120) for the location at 35 miles downwind from a 1-MT yield surface detonation where I(1) was 2000 r/hr at 1 hour. For the 2000 r/hr at 1 hour level located at about 6 miles downwind for that detonation, the estimated exposure dose from time of fallout arrival to 1 day after detonation is 6500r; for this location, the required value of RN_1 is 0.0046 (1/216). Since the maximum ionization rate levels from the 1-MT yield land surface detonation are not much larger than the 2000 r/hr at 1 hour level (except for a small area in the downwind direction near ground zero), a shielding factor of 0.001 would provide sufficient radiation protection from the fallout produced by about 8 1-MT yield weapons, detonated at the same location, to keep the exposure dose from exceeding the assumed value of D*. Thus if shelter spaces with RN_1 values in the ranges of 0.001 to 0.01 are assumed to be available for these levels of fallout, it is appropriate to discuss the shelter stay time. Also, the only relationship in which the shelter stay time depends on RN_1 is that given by Eq. 11.3 and the only procedure by which the stay time can be estimated is through substitution of appropriate values of D* in that equation.

Assuming that the shelter is available and adequate --i.e., $D^* >> RN_1 D_i$-- the minimum stay time in shelter is determined from the suggested values of D*, by the time at which the outside exposure dose is 30r in 1 day or 1000r in 1 year. In this definition, the minimum shelter stay time refers to continuous shelter occupancy and, continuous stay in the immediate area after coming out of shelter. However, the method for calculating the minimum shelter stay time can be applied to any assumed exposure period out of shelter.

The computational procedure for estimating the minimum shelter stay time utilizes Figure 11.1. First the values of DRM are taken from the curve at several values of the entry time, t_e, and of $t_e + \Delta t$, where Δt is the assumed or desired exposure period; second, the values of t_e are plotted as a function of the differences, ΔDRM, between the DRM values at each pair of times as shown in Figure 11.3. For occupants of a shelter, the entry time (after detonation) may be the same as the shelter exit time; in general, the entry time refers to the time after attack when entry is made into a fallout area of reasonably high radiation intensities.

Figure 11.3
VARIATION OF EXPOSURE AREA ENTRY TIME, t_e, WITH Δ DRM FOR SELECTED VALUES OF STAY TIME IN A FALLOUT AREA



Corresponding values of the true air ionization rate at H+1, I_a (1), $I_a(1) = 1.33I(1)$ are then calculated from

$$I_a(1) = D^*/\Delta DRM \qquad (11.4)$$

where ΔDRM is read from the curve at selected values of t_e. The values of $I_a(1)$ for the selected set of D* values, plus those for a D* value of 200r in one week, are shown in Figure 11.4. The curves show that the D* value of 30r in 1 day controls the shelter-stay time for $I_a(1)$ values up to about 1300 r/hr at 1 hour and the shelter stay times up to 250 hours (about 10 days). The 1000r in 1 year D* value controls the stay time for the higher levels and longer shelter stay times. The minimum shelter stay time, for an I(1) of 2000 r/hr at 1 hour, therefore is 690 hours, or about 29 days. The minimum shelter stay time for the 10,000 r/hr at 1 hour level is 4900 hours, or slightly under 7 months.

The required shelter stay times are extremely long for the higher levels under the conditions that both RN_2 and RN_3 are unity and the value of RN_1 is essentially zero. The minimum shelter stay time is decreased when decontamination is included in the countermeasure system. The shelter stay times for shelter occupants who are not a member of a decontamination crew are estimated through Eq. 11.3 by neglecting the $RN_2 D_2$ term. The general expression for $I_a(1)$ then becomes

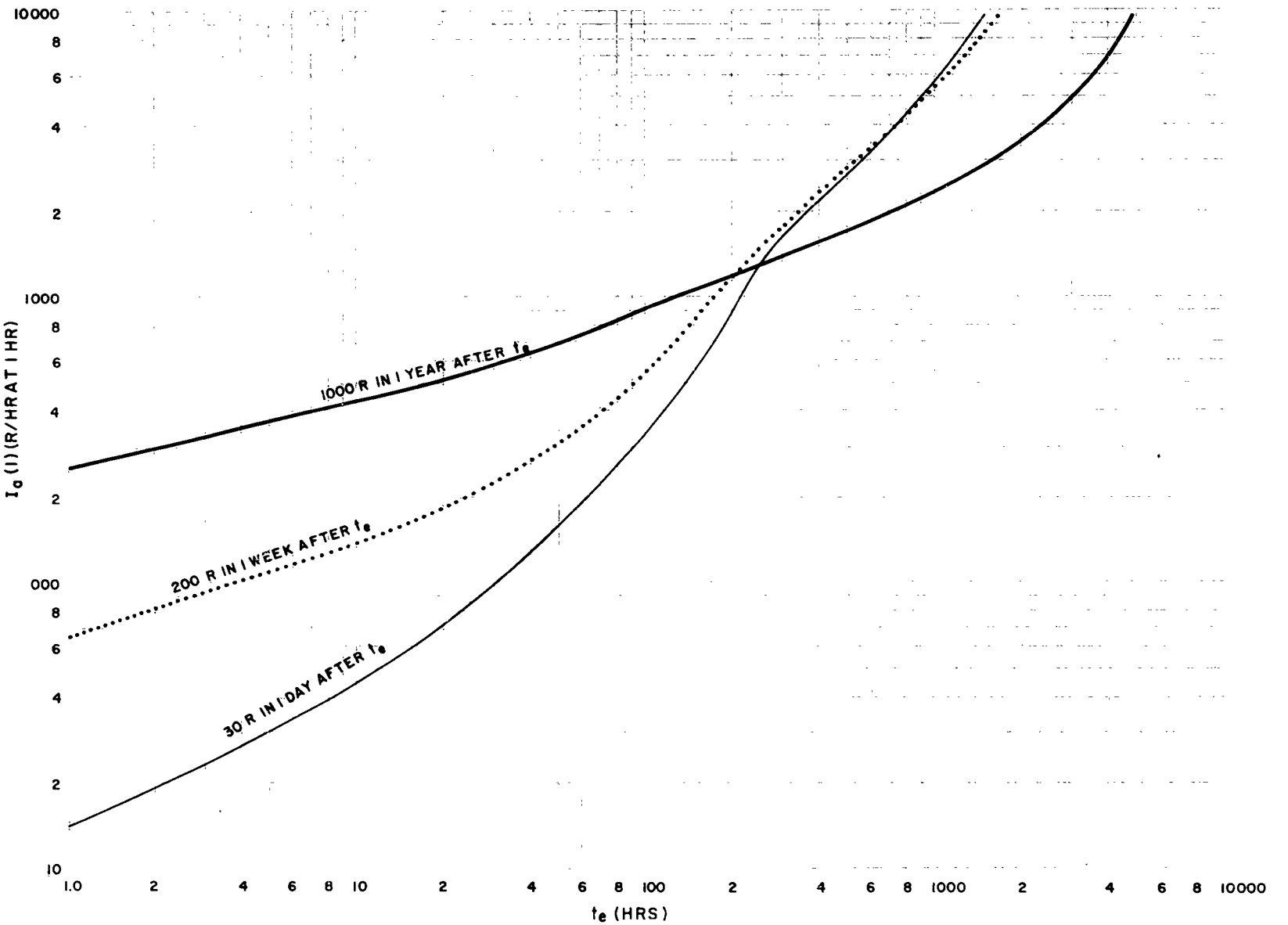
$$I_a(1) = D^*/RN_3 \Delta DRM \qquad (11.5)$$

Thus RN_3 is simply a multiplying factor to $I_a(1)$ of Eq. 11.4 and Eq. 11.5 can be evaluated by use of Figure 11.4.

If a shelter stay time no longer than a week is desired then, from Figure 11.4, $I_a(1)$ for 30r in 1 day is 670 r/hr at 1 hour; then RN_3, for the 2000 r/hr at 1 hour location, must be 670/2000 or 0.335. Similarly, RN_3 for the 10,000 r/hr at 1 hour location (if it exists) is 670/10,000 or 0.067. It is seen that only by removing 2/3 of the fallout (or less if building shielding is accounted for), the shelter stay time at the 2000 r/hr at 1 hour location is reduced by a factor of 4; and, if 93 percent is removed at the 10,000 r/hr at 1 hour location the shelter stay time is reduced by a factor of 29. Other countermeasure actions such as evacuation to areas of lower fallout levels, if they are not too far away, may be employed to shorten shelter stay time.

For any selection of D*, the minimum shelter stay time increases very rapidly with $I_a(1)$ when $I_a(1)$ is large, because the gross decay rate of the

Figure 11.4
VARIATION WITH $I_a(1)$ OF THE REQUIRED SHELTER STAY TIMES, OR TIMES OF ENTRY INTO THE FALLOUT AREA, FOR A STATED STAY TIME BASED ON ASSUMED D* VALUES OF 30 r IN 1 DAY, 200 r IN 1 WEEK, AND 1000 r IN 1 YEAR AFTER THE TIME OF ENTRY



fission products in fallout decreases with time. The slower decay rate at the longer times after detonation is responsible for the fact that modest values of RN_3 can result in large decreases in the required shelter stay times.

11.5 The Maximum Decontamination Residual Number

The maximum value of the decontamination residual number, RN_3, based on a selected value of D* can be determined in a general way only if a dual set of D* values are available. One set then applies to the people who are not involved in decontamination operations and the other set applies to the decontamination crew. If only one set of D* values is used, then both RN_2 and RN_3 must be solved for simultaneously. There may be cases, however, where both RN_2 and RN_3 have compatible values depending on how D* is defined.

The simplest case to consider is where RN_1 is very small (0.001 or less). This case is described by Eq. 11.5, which can be rewritten as

$$RN_3 = \frac{D^*}{I_a(1)\,\Delta DRM} \tag{11.6}$$

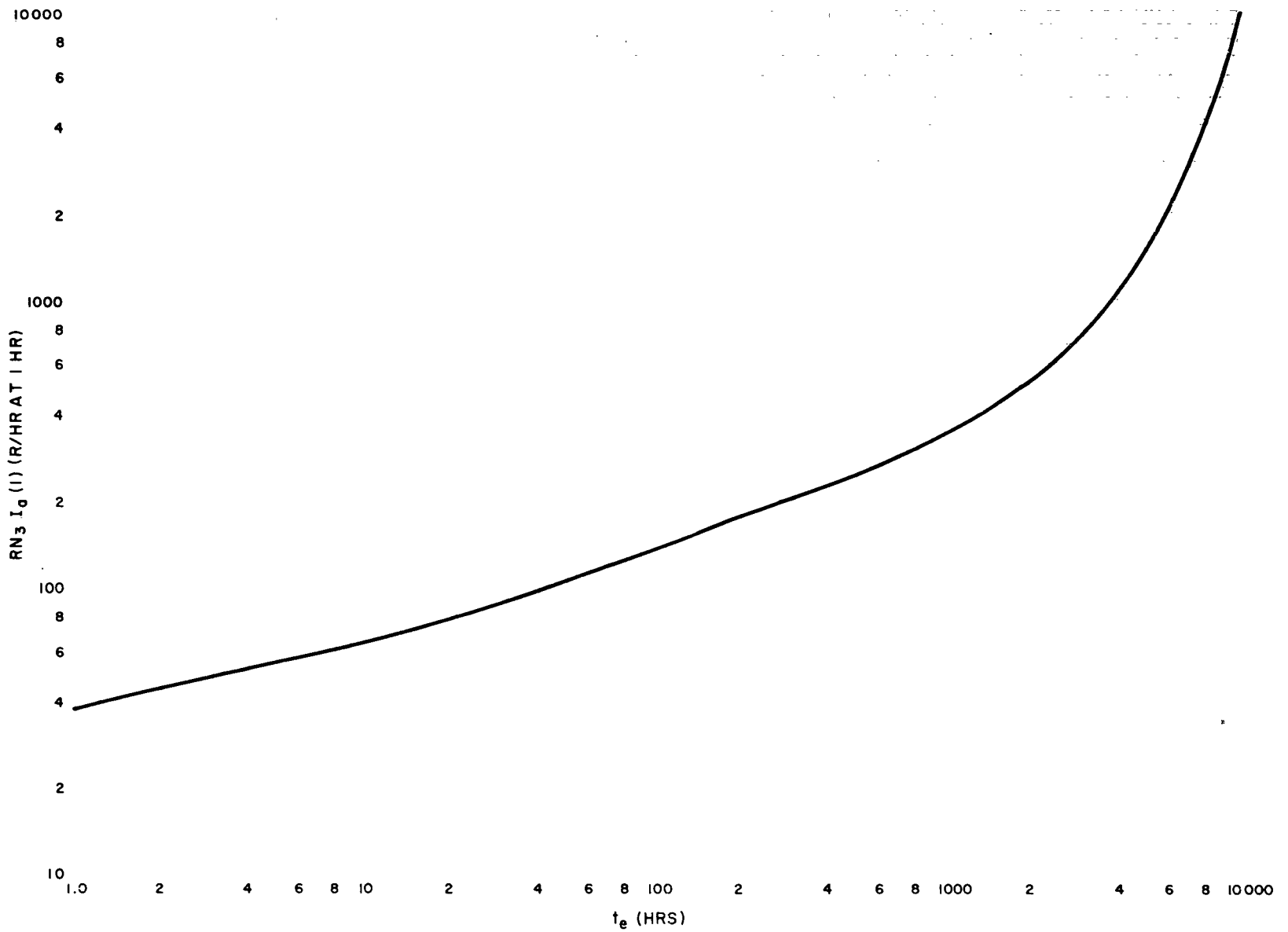
The values of the product, $RN_3 I_a(1)$, are the same as those of $I_a(1)$ in Figure 11.4 for the previously stated designation of D*. The lower of the curves can be used to obtain RN_3 either for a given entry time as a function of $I_a(1)$ or for a given value of $I_a(1)$ as a function of entry time.

A more conservative definition of D* is to extend the time period of its applicability; a commonly used definition is to give D* in terms of a limit to the infinity exposure dose. For this kind of definition of D* Eq. 11.6 is rewritten as

$$RN_3 = \frac{D^*}{I_a(1)\left[3.946 - DRM(t)\right]} \tag{11.7}$$

The values of $RN_3 I_a(1)$, assuming the infinity dose of 150r for D* (which is a conservative planning dose compared to 1000r in 1 yr), are shown in Figure 11.5. For the location at which I(1) is 2000 r/hr at 1 hr, $I_a(1)$ is 2,660 r/hr at 1 hr, t_e is one week, and D* is 30r in 1 day, then residual number, RN_3, is 0.25; the selection of 150r to infinity for D* gives an RN_3 value of 0.062. For an entry time of 2 weeks, the two respective values of RN_3 are 0.55 and 0.079. These different values of the maximum, or required, decontamination residual number indicate its dependence on both the definition of D* and on the entry time.

Figure 11.5
VARIATION OF $RN_3I_a(1)$ WITH ENTRY TIME INTO THE FALLOUT AREA FOR AN ASSUMED D* VALUE OF 150 r FROM ENTRY TIME TO INFINITY



To investigate the relation between RN_1 and RN_3 for the cases where RN_1 is not negligible without first computing a wide range of D_1 values from the time-of-arrival curves from different yield weapons, requires an assumption about the fallout arrival for estimating D. The assumption used here, for a set of illustrative computations, is that the "effective" fallout arrival time is one hour after detonation. This assumption is more valid for a given downwind distance than for a stated value of I(1); it represents approximately the locations in the fallout area along a line perpendicular to the downwind direction of the fallout pattern.

It has already been shown, for the successive allotments of 30r in 1 day at two different times after detonation at the 2000 r/hr at 1 hour locations 6 and 35 miles from the 1-MT land detonation, that the values of RN_1 and RN_3 were not interdependent. In other words, the value of each residual number was determined separately from the definition of D*. This independence of RN_1 and RN_3 on the value of each other will always result when the value of D* is given as a 1-day exposure dose and the entry time is more than 1 day after detonation.

For the 1-hour effective fallout arrival time, and the 30r in 1 day definition of D*, the required shelter residual number is

$$RN_1 = 14.1/I_a(1) \tag{11.8}$$

and, for entry times less than 1 day,

$$RN_1 + RN_3 = 14.1/I_a(1) \tag{11.9}$$

For $I_a(1)$ values as high as 30,000 r/hr at 1 hour, RN_1 values, according to Eq. 11.8 of about 0.005 (1/2,000) are required. Since the RN_1 values are determined from the definition of D* and the DRM curve derived from a decay curve, the short-time definition of D* will usually control the required value of RN_1. For example, if the exposure dose is 30r in first day after fallout arrival, the exposure dose is less for any succeeding day and is always less than 1,000r in a year, for a given value of RN_1.

For the 1,000r in a year value of D*, the values of RN_1 and RN_3 do depend on each other (except for shelter stay times or entry times of a year). The interdependence of RN_1 and RN_3, for this definition of D* and the 1 hour effective arrival time, is given by

$$1000/I_a(1) = RN_1 DRM(t) + RN_3 (3.946 - DRM(t)) \tag{11.10}$$

The maximum values of both RN_1 and RN_3 from Eq. 11.10 will be the limiting values of the two residual numbers only for the higher values of $I_a(1)$ and for the lower values of RN_1 because of the prior restriction of the D* value of 30r in 1 day. The values of RN_1 and RN_3 obtained from the combination of the two definitions of D* are given in Table 11.2 for an entry time of 2 weeks.

The characteristic solution of Eqs. 11.9 and/or 11.10 is that no solutions are possible for RN_1 values greater than about 0.01, and, for RN_1 values less than 0.01, the no-solution cases slide to higher values of $I_a(1)$ as RN_1 decreases. Also, no decontamination is required for fallout levels less than 1,000 r/hr at 1 hour where solutions are possible. But at the higher levels of $I_a(1)$ for each RN_1 value, the required RN_3 value goes to zero at the point where no solution is possible. If entry times earlier than 250 hours are considered, RN_3 is controlled by the 30r in 1 day D* value.

From the RN_3 requirements of Table 11.2, it is clear that the excessively large 1,000r in 1 year planning dose can be met by use of the available radiological recovery countermeasures. But it is preferable, when possible, to minimize the exposure dose. To investigate the requirements of the more conservative planning dose, the values of RN_1 and RN_3, for a D* value of 150r to an infinite time (2.3 years) were determined for the one hour effective arrival time. The boundary condition for this definition of D* leads to

$$150/I_a(1) = RN_1 DRM(t) + RN_3 \left[3.946 - DRM(t)\right] \qquad (11.11)$$

For the exposure doses calculated for 35 miles downwind from the 1-MT yield detonation where $I_a(1) = 2660$ r/hr at 1 hour, Eq. 11.11 becomes

$$150 = RN_1 D_1 + RN_3 (8460 - D_1) \qquad (11.12)$$

The values of RN_3 calculated from Eq. 11.12 at several selected entry time values and RN_1 values are listed in Table 11.3. The RN_3 values less than zero are indicated as giving no feasible solution of Eq. 11.12; these, in general, occur for RN_1 values less than 0.01, except at the early entry times. Also, the RN_3 values required for the 150r infinity dose for D* are essentially a step function, with respect to their change with RN_1; there is only a small increase in RN_3 as the value of RN_1 decreases from about 0.01 to 0.0005.

The calculations for the 150r infinity dose also show that, if RN_1 is sufficiently low, decontamination countermeasures with RN_3 values between 0.02 and 0.06 would permit entry times from 6 hours to 1 week after detonation for fallout levels of 2,000 to 3,000 r/hr at 1 hour. The exact entry time possible

Table 11.2

VALUES OF RN_1 AND RN_3 FOR AN ENTRY TIME OF TWO WEEKS FOR AN ASSUMED EFFECTIVE ARRIVAL TIME OF ONE HOUR AFTER DETONATION

RN_1	Max. $I_a(1)$ (r/hr at 1 hr)	$I_a(1)$				
		1,000	2,000	5,000	10,000	20,000
		RN_3 [a]				
0.5	28	---------- No solution possible ----------				
0.1	141	---------- No solution possible ----------				
0.05	282	---------- No solution possible ----------				
0.01	1,410	1.0	No solution possible ----------			
0.005	2,820	1.0	0.714	No solution possible ----------		
0.001	14,100	1.0	0.733	0.220	0.143	No --
0.0005	28,200	1.0	0.735	0.293	0.145	0.071
RN_1 for 30 r in 1st day		0.014	0.0070	0.0028	0.0014	0.00070
RN_3 for 30 r in 1 day (at 2 weeks)		1.0	0.925	0.370	0.185	0.0925

a. For 1000 r in 1 year after H + 1.

Table 11.3

CALCULATED VALUES OF RN_3 FOR 150R INFINITY DOSE, AT SELECTED ENTRY TIMES AND RN_1 VALUES[a]

t_e (hrs)	RN_1							RN_1^b
	0.5	0.1	0.05	0.01	0.005	0.001	0.0005	
6	c	0.0	0.011	0.019	0.020	0.021	0.021	0.10
12	c	c	0.0004	0.021	0.023	0.025	0.025	0.058
24	c	c	c	0.023	0.027	0.030	0.030	0.042
48	c	c	c	0.027	0.032	0.037	0.038	0.032
96	c	c	c	0.031	0.040	0.047	0.048	0.028
168	c	c	c	0.037	0.050	0.060	0.061	0.025
336	c	c	c	0.044	0.062	0.075	0.077	0.023
720	c	c	c	0.047	0.081	0.102	0.105	0.021

a. For $I_a(1) = 2660$ r/hr at 1 hr, 35 miles downwind from a 1-MT yield surface detonation.

b. For $RN_3 = 0$

c. No solutions possible.

would depend on both the planning dose for the decontamination crews and on the time it would take to carry out the decontamination procedure.

11.6 The Maximum Exposure Period for Recovery Crews

The maximum exposure period, designated as $\Delta t_d(\max)$, is the longest decontamination working-time that is calculated for a given value of the crew exposure dose. In planning calculations, $\Delta t_d(\max)$ is the difference between the entry time and the decontamination starting time.

To determine $\Delta t_d(\max)$, for a given decontamination operation, through Eq. 11.3, usually requires prior specification of the values of RN_1, RN_2, and RN_3 and of the decontamination working-time to achieve RN_3. The only general case for which determinations of $\Delta t_d(\max)$ would be useful are those where the value of RN_1 (for the decontamination crews) is small. In this case, the important parameter of Eq. 11.3 for evaluating $\Delta t_d(\max)$ is RN_2; the value of RN_2, in turn, depends on the value of RN_3, on characteristics of the area being decontaminated, and on various characteristics of the decontamination procedure(s). Important procedure characteristics include such factors as the rate of application, the efficiency of the method, equipment shielding, and the scheduling-sequence of the method.

A few of the considerations involved in estimating RN_2 are illustrated by calculations, such as those used by H. Lee[3], for a simple decontamination procedure in which a firehosing crew decontaminates a circular paved area about 500 feet in radius (800,000 sq ft). If the 5-man crew operates at a rate of 30 man-minutes per 10^4 feet (1,670 sq ft /min), about 480 minutes, or 8 hours, are required to decontaminate the area. The crew starts the decontamination in the center of the area where it is initially exposed to the ionization rate, $I(t)$; then, as the crew works outward from the center, the ionization rate to which it is exposed decreases because of the increase in the central clean area. When a circle with a radius of about 150 feet is cleaned, the crew is no longer exposed to radiation from the fallout that lies outside the cleaned area and directly across the diameter of the circle[5]. By the time the clean area is expanded to about half the total area to be cleaned (i.e., to a radius of about 350 feet), the crew is exposed mainly to the radiation from particles lying on the surface area that is nearest to the crew but is outside the cleaned area.

Assuming that, during the decontamination, the decrease with time of $I(t)$ is linear for the first half of the total working-time, and that, for the second half of the working-time, 50 percent of the exposure dose is from radiation from the clean area and 50 percent from the uncleaned area, then the ionization

rate to which the crew is exposed during the operation is

$$I'(t) = I(t)\left[1 - (1-RN_3)t/t_o\right], \quad t = 0 \text{ to } 1/2\ t_o \tag{11.13}$$

and

$$I'(t) = (I(t)/2)\left[1 + RN_3\right], \quad t = 1/2\ t_o \text{ to } t_o \tag{11.14}$$

where t_o is the time required to carry out the operation. If I(t) is assumed constant over the period, the exposure dose during the decontamination, from integration of I(t)dt, is

$$RN_2 D_2 = (5 + 3RN_3)\ I(t)t_o/8) \tag{11.15}$$

And, since I(t) t_o is the approximation of D_2, the decontamination crew residual number is

$$RN_2 = 0.62 + 0.38RN_3 \tag{11.16}$$

Other ways of estimating RN_2 for different decontamination methods, and some experimentally derived values of RN_2, are given in Chapter 12. However, Eq. 11.16, for the assumed decontamination procedure, shows the dependence of RN_2 on RN_3 and is used to further illustrate the computational methods and concepts regarding the application of RN_2 in estimating $\Delta t_d(max)$. If equipment shielding is considered for a method, the first term on the right of Eq. 11.16 is replaced with $0.62A_e$, where A_e is the attenuation factor for the equipment operator.

If the decontamination crew(s) are to occupy the decontaminated area for a long time after t_e, the decontamination residual number, RN_3, that they must achieve is determined by substitution of Eq. 11.16 for RN_2 in Eq. 11.3 and setting $RN_1 D_1$ equal to zero. The upper-limit value of RN_3 is then

$$RN_3 = \frac{D^* - 0.62\ A_e D_2}{D_3 + 0.38\ A_e D_2} \tag{11.17}$$

where D* is the planning dose from the starting time of decontamination to infinity.

If a special, or emergency, planning dose is prescribed for either the whole decontamination period or some portion of it, then the planning dose restraint can be expressed as

$$D^* = RN_2 D_2 \tag{11.18}$$

or, with Eq. 11.16, as

$$D^* = (0.62A_e + 0.38\ RN_3)\ D_2 \tag{11.19}$$

for the above described operation. The planning dose of 30r in 1 day would be almost a special planning dose if the decontamination crews had good shelters; in the above illustration, this situation would be almost the same as 30r in 8 hours, provided the crews returned to shelter or to the center of the cleaned area for the remaining 16 hours.

When the starting time of a decontamination operation is based on a 8-hour definition of the planning dose with a 16-hour non-exposure following period, the planning dose could never be exceeded on any following 8-hour work day unless the crews were sent to areas having higher fallout levels. For crews and methods involving equipment that could be operated longer than 8 hours, D* could be defined for a somewhat longer time. And if three shifts of operators were available, continuous operations could actually be maintained, the same planning dose can be used in estimating both Δt_d (max) and the starting time of a recovery operation.

If the value of RN_3 in Eq. 11.19 is less than about 0.1 for a given method, the small contribution of $0.38\ RN_3$ can be either added to $0.62A_e$ as a constant or neglected; for these cases, the maximum value of $I_a(1)$ for starting decontamination at the time after detonation, t_{dec}, can be estimated from

$$I_a(1) = \frac{1.52\ D^*}{A_e \Delta DRM(8h)} \tag{11.20}$$

where $\Delta DRM(8h)$ is the difference in the dose rate multiplier for a time period of 8 hours. To determine $I_a(1)$ from Figure 11.3, the value of t_{dec} for Eq. 11.20 is the same as t_e of Figure 11.3.

The definition of D* in Eq. 11.17 for a time period from t_{dec} to infinity requires solving for the maximum exposure period of decontamination from a set value of ΔDRM values given by

$$\Delta DRM = \frac{D^* - RN_3 D_3}{A_e I_a(1)\,(0.62 + 0.38\,RN_3)} \tag{11.21}$$

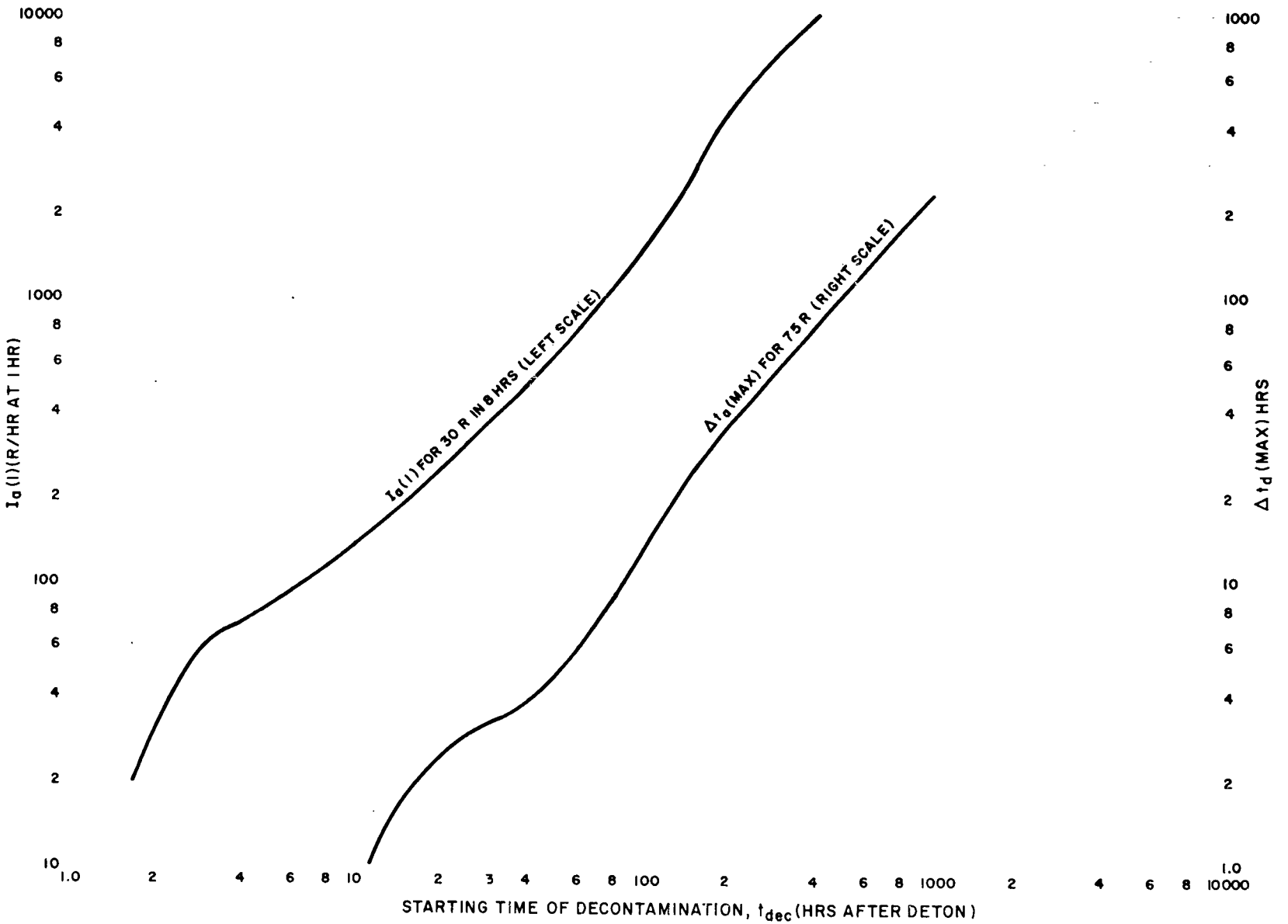
The value of RN_3 in Eq. 11.21 must satisfy the planning dose restrictions set for both the decontamination crews and the remainder of the population that does not participate in decontamination. If the planning dose for general population is lower than that for the recovery crews, then the planning dose for the population is used to determine the value of RN_3. This is done separately through Eq. 11.11. A further constraint on the exposure of crews during decontamination is to assign no more than a stated fraction of the planning dose to the recovery period. For example, if 0.5 D* is selected as this fraction, 150r to infinity for D*, 2660 r/hr at 1 hour for $I_a(1)$, 0.05 for RN_3 (as required, according to Table 11.2, for an entry time of about 4 days with RN_1 values of 0.001), and 1.0 for A_e, then the difference in DRM for the maximum exposure time for the crews is

$$\Delta DRM = 0.044 \tag{11.22}$$

The maximum exposure periods for the conditions of Eq. 11.22 are determined from the dose rate multiplier curve as follows: (1) select a series of possible values of t_{dec}; (2) read the DRM value for the t_e value equal to the selected t_{dec}; (3) add 0.044 to DRM; (4) read the time, t_e, for the new value of DRM; and (5) plot the difference in the two times, Δt_d(max), as a function of t_{dec}. The values of Δt_d(max) for both Eq. 11.22, and of $I_a(1)$ for Eq. 11.20, are plotted as a function of t_{dec} in Figure 11.6. Both curves assume that no decontamination is started before fallout cessation, even though the initial parts of the two respective curves start at about 2 hours and 10 hours after detonation.

For the planning dose of 30r in 8 hours the decontamination starting times are not dependent on the time required to do the decontamination. From the $I_a(1)$ curve, the starting time for 2660 r/hr at 1 hour is 150 hours (6-1/4 days). The D* value of 75r for the decontamination crews during recovery results in specified longer maximum exposure periods for carrying out a decontamination operation the later it is started. An 8-hour decontamination job, for example, could be started at about 77 hours after detonation and the entry time would be 85 hours after detonation.

Figure 11.6
VARIATION OF MAXIMUM VALUES OF $I_a(1)$ FOR A D* VALUE OF 30 r IN 8 HOURS AND MAXIMUM EXPOSURE TIMES FOR DECONTAMINATION CREWS FOR A D* OF 75 r DURING DECONTAMINATION (for $I_a(1)$ = 2660 r/hr at 1 hr) WITH THE TIME AFTER DETONATION AT WHICH DECONTAMINATION OPERATIONS CAN BE STARTED



11.7 The Minimum Entry Time with Decontamination

The minimum entry time for an area that has been decontaminated are determined directly from the RN_3 value derived from a definition of the planning dose, the value of RN_2 for the various decontamination crews (and the crew planning dose), and the efficiency of the selected decontamination methods.

To illustrate the relationship among the various parameters on which the minimum entry time with decontamination depends, several equations and computations are summarized below for the following assumed planning conditions:

1. $I_a(1) = 2660$ r/hr at 1 hour
2. The surface to be decontaminated is 10^6 sq ft of asphalt pavement
3. The methods available are either one Wayne model 450 street sweeper or one 5-man firehosing crew
4. Both the decontamination crew and the population that will occupy the area after decontamination are assumed to have good shelters so that the exposure dose of $RN_1 D_1$ can be neglected
5. D* for the population is either 30r in 1 day (1000r in 1 year) or 150r from entry time to infinity (2.3 years)
6. D* for the decontamination crews is either 30r in 8 hours, or 75r for the entire decontamination operation
7. The shielding attenuation factor, A_c, is assumed to be unity
8. The effect of building shielding on the value of the parameters is not considered.

Equation 11.19 is used in this example for estimating RN_3 rather than the simplified form given by Eq. 11.20. Since $I_a(1)$ is defined and the decontamination starting time depends on RN_3, it is convenient to derive the decontamination starting time, for arbitrarily selected values of RN_3, from

$$\Delta DRM(8h) = \frac{0.0113}{0.62 + 0.38RN_3} \tag{11.23}$$

and the curve of Figure 11.3 for a Δt_{dec} of 8 hours. Equation 11.23 is a rewrite of Eq. 11.19 with D* equal to 30r and $I_a(1)$ equal to 2660 r/hr at 1 hour.

Application of the decontamination efficiency equations and other data of Chapters 9 and 10 in estimating the decontamination effectiveness requires an estimate of mass of fallout particles per unit area for the selected value of $I_a(1)$, which is the same as an I(1) value of 2000 r/hr at 1 hour. The fallout mass surface density is obtained from the $M_r(1)$ values of Table 6.8 (see Volume I) for a 1-MT surface detonation; $M_r(1)$ is about 4.7 (mg/sq ft)/(r/hr at 1 hour). Hence

$$y = I(1)M_r(1) = 9.4 \text{ gm/sq. ft.} \tag{11.24}$$

The decontamination equation constants for firehosing are: $3K_o = 1.26$, and $R_M = 2.00$; M*, from Eq. 9.2 and Table 10.2, is

$$M^* = 0.070\, y^{0.63} \tag{11.25}$$

The decontamination equation of the fraction remaining (from Eq. 9.23) for firehosing is then

$$F = 0.0305 + 0.969\, e^{-1.26\, E^{1/3}} \tag{11.26}$$

For the 10^6 sq ft area, the working time associated with the effort, E, in man-min/10^4 sq ft, is

$$\Delta t_{dec}(\text{hrs}) = 0.33E\,. \tag{11.27}$$

The decontamination equation constants for the motorized sweeper are: K = 0.330, $R_m = 1.95$, $k_f = 0.025$, and M* = 0.287. With these constants, the equation of the fraction remaining (from Eq. 9.15) for motorized sweeping is

$$F = 0.0436 + 0.996e^{-0.330\, E} \tag{11.28}$$

The time of operation associated with E in Eq. 11.28 for the area is

$$\Delta t_{dec}(\text{hrs}) = 1.67E \tag{11.29}$$

If other crews decontaminated the area around the periphery of the selected area to the same degree as the selected area is decontaminated, then the F values of Eqs. 11.26 and 11.28 can be replaced by RN_3. Otherwise, due to the radiation from surrounding contaminated areas, the F values would only approach the defined values of RN_3 for the central portion of the cleaned area (providing the width of the area is more than about 300 ft).

In real planning estimates, the decontamination working times computed from such Eqs. as 11.27 and 11.29 are not used as the estimate of the total decontamination time; equipment set-up times, delay times of one sort or another, the time spent in running the sweeper to and from a dumping area, and the time required to assemble the crews must also be included. The value of Δt_{dec} that is directly related to E, then, is the actual time spent by the crew in doing decontamination work. For the illustration, these additional times are neglected. The purpose of the calculations here is merely to show the nature of the mathematical solution. The additional times depend a great deal on local conditions such as where the hydrants are, how far away the dumping area is, and how fast a crew can assemble its equipment and put it into action. For the firehosing, it is assumed that storm drains are located about 200 feet apart to eliminate consideration of variation in the remaining level with distance of travel (see Chapter 10).

The computated values of various decontamination parameters, for cleaning the 10^6 sq ft area of asphalt pavement by firehosing and motorized sweeping at selected values of E, are summarized in Table 11.4 (assuming that the F values of Eqs. 11.26 and 11.28 are equal to RN_3 of Eq. 11.23). The derived values of t_{dec} are based on a D* of 30r in 8 hours to the crew having no equipment shielding.

Actually, the calculation for Table 11.4 is more elaborate than is usually necessary. In firehosing, for example, there is a practical limit in forward speed for moving the bulk of the particles along; the fastest forward speed used in the data from which the decontamination equation constants were derived was about 70 ft/min for an area 40 feet wide. Thus, assuming that the same surface coverage could be obtained at twice that forward speed for a 50 foot wide strip, then the maximum forward speed would be about 150 ft/min, or an area coverage rate of about 7500 sq ft/min; with this rate as a maximum, the shortest time for cleaning the 10^6 sq ft area would be about 2 hours.

The Wayne 450 motorized sweeper with a 58 inch broom could be operated to sweep strips that average about 4.5 feet in width; thus, in sweeping the 10^6 sq ft, the sweeper would travel 42 miles. At 5 mph it, would sweep the area once in 8.4 hours or twice in 16.8 hours. In a higher gear, traveling at 7.5 mph, the shortest time for one cycle over the area would be 5.6 hours. Thus, with set speeds, only certain values of F and E are possible. Other values of F and

Table 11.4

ESTIMATED DECONTAMINATION STARTING TIMES, WORKING-TIMES, AND ENTRY TIMES FOR DECONTAMINATING 10^6 SQ FT OF ASPHALT PAVING BY FIREHOSING AND MOTORIZED SWEEPING[a]

Firehosing						Motorized Sweeping				
$\left(\frac{E^b}{\frac{\text{man-min}}{10^4 \text{ sq ft}}}\right)$	F	Δt_{dec} (hrs)	ΔDRM(8hr) (hr)	t_{dec} (H+hr)	t_e (H+hr)	F	Δt_{dec} (hrs)	ΔDRM(8hr) (hr)	t_{dec} (H+hr)	t_e (H+hr)
0.25	0.47	0.08	0.0142	182	182	0.92	0.42	0.0117	204	204
0.50	0.39	0.17	0.0147	178	178	0.89	0.83	0.0118	203	204
0.75	0.34	0.25	0.0151	176	176	0.82	1.25	0.0121	202	203
1	0.31	0.33	0.0154	172	172	0.76	1.7	0.0124	198	200
2	0.23	0.67	0.0160	168	169	0.56	3.3	0.0136	187	190
3	0.19	1.0	0.0164	167	167	0.41	5.0	0.0146	180	185
4	0.16	1.3	0.0166	164	165	0.31	6.7	0.0153	174	181
5	0.14	1.7	0.0168	163	165	0.24	8.3	0.0159	168	176
6	0.13	2.0	0.0169	162	164	0.18	10	0.0164	165	175
7	0.12	2.3	0.0170	162	164	0.14	12	0.0168	163	175
8	0.11	2.7	0.0171	161	164	0.11	13	0.0170	162	175
9	0.10	3.0	0.0172	160	163	0.094	15	0.0172	160	175
10	0.094	3.3	0.0172	159	162	0.080	17	0.0174	158	175
15	0.074	5.0	0.0174	158	163	0.051	25	0.0177	156	181
20	0.062	6.7	0.0176	157	164	0.045	33	0.0177	155	188
30	0.050	10.0	0.0177	157	167					
40	0.043	13	0.0178	156	169					
60	0.036	20	0.0179	156	176					
80	0.034	27	0.0179	156	183					
100	0.033	33	0.0179	156	189					

a. I(1) =2000r/hr at 1 hr, at 35 miles from A 1-MT Yield Surface Detonation.

b. Man-min and equipment-min are the same (1 operator) for motorized sweeping.

E could be obtained by deliberately spacing the sweeping passes so that some of the area is missed; or, on the second cycle, all the additional effort could be used in resweeping hot spots or spills from the first cycle.

The RN_3 values required for a D* of 30r in 1 day for the population and for 30r in 8 hours for the crew members are given as a function of entry time in Figure 11.7. The exact solution of the entry time, the decontamination starting time, the effort required, and the required value of RN_3 are determined from the intersections of the decontamination RN_2 (or F) curves with the curve based on the planning dose for those occuping the area after t_e.

The RN_3 curves for the two decontamination methods show the dependence of RN_3 on the dose to the crew for an 8 hour period. All points on the curves, except the point for a Δt_{dec} of 8 hours, are not precisely correct for 30r in 8 hours to the crew; for Δt_{dec} values less than 8 hours, the exposure dose will be less than 30r, and, for Δt_{dec} values greater than 8 hours, the exposure dose of the crew will be greater than 30r, unless the operators are replaced after 8 hours work, as mentioned previously.

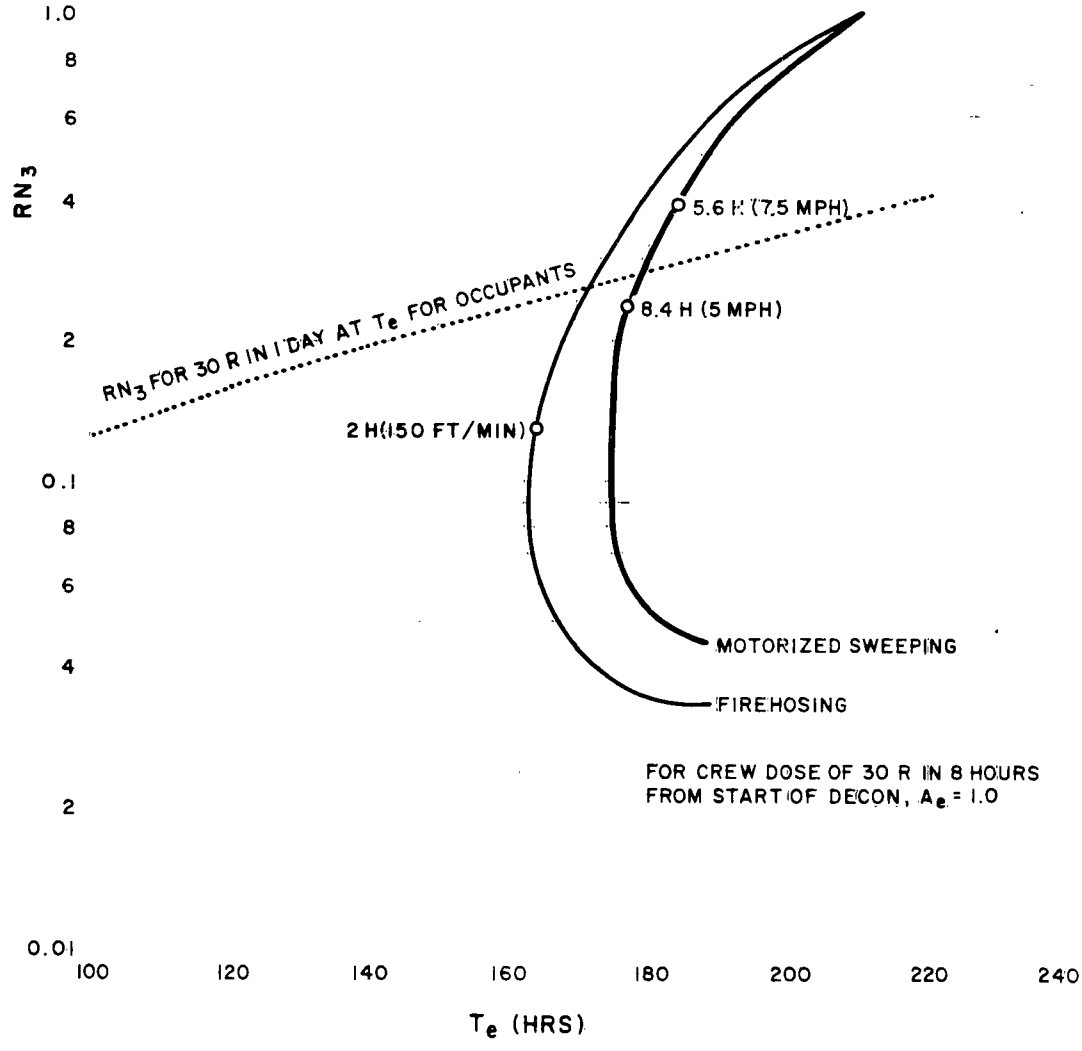
For the particular value of $I_a(1)$ chosen, the earliest entry times achievable with decontamination giving lower RN_3 values than required by the population planning dose. Thus, firehosing by a crew of 5 men for about 3 hours would permit an entry time of about 163 hours (6.8 days) at an RN_3 value of 0.1 which is about a factor of 2.5 less than required. The earliest entry time with motorized sweeping by one man would be obtained with about 2 sweeping cycles at an entry time of 175 hours (7.3 days). The normal entry time without decontamination, based on a D * of 1000r in 1 year for an $I_a(1)$ value of 2660 r/hr at 1 hour, is 1250 hours or 52 days.

The entry times and RN_3 values for a D* of 150r from t_e to infinite time for the occupants of the area, 75r to each crew member during the decontamination work, and the decontamination efficiency curves for the two methods are shown in Figure 11.8.

The RN_3 values for the D* value of 150r from t_e to infinity are calculated by dividing the curve of Figure 11.5 by 2660. The decontamination RN_3 values are obtained by using the appropriate F and Δt_{dec} values of Table 11.4; the corresponding values of t_e are determined by summing the paired values of Δt_{dec} and t_{dec} from Figure 11.6. The more conservative planning dose (150r from t_e to infinity) requires more thorough decontamination; however, the slightly more liberal planning dose for the decontamination crew members permits a solution for t_e that is even lower than the t_e of Figure 11.7.

To achieve an RN_3 value of 0.05, with firehosing and an entry time of 100 hours (4.2 days), the decontamination working time is 10 hours. For this

Figure 11.7
ESTIMATED CLEARED AREA ENTRY TIME AND REQUIRED VALUE OF RN_3 FOR FIREHOSING AND MOTORIZED SWEEPING DECONTAMINATION OF 10^6 SQUARE FEET OF ASPHALT PAVEMENT, WHERE $I_a(1)$ IS 2660 r/hr AT 1 hr AT 35 MILES DOWNWIND FROM A 1-MT YIELD DETONATION, ASSUMING A WIND SPEED OF 15 MPH



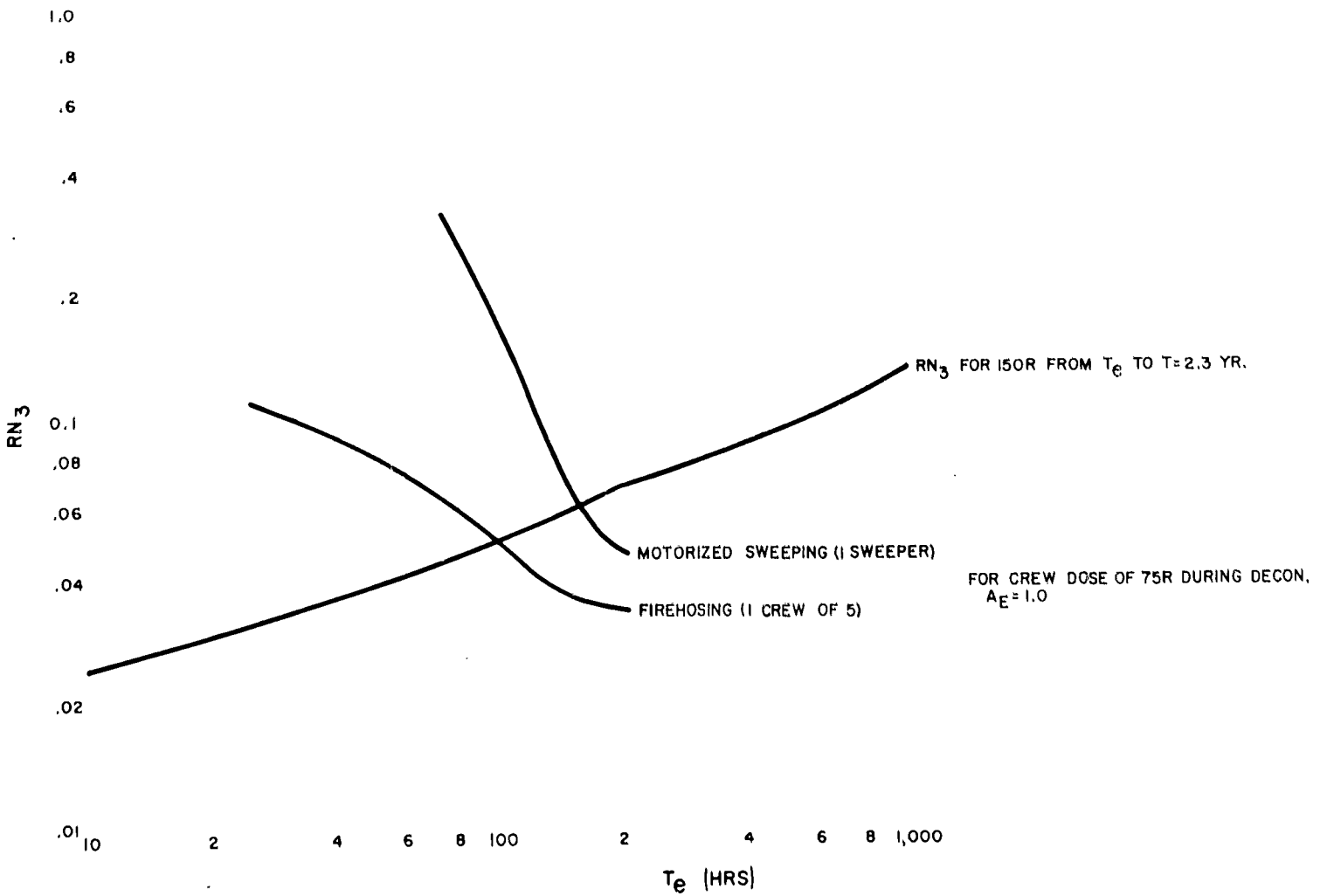
effort, the forward speed of decontamination, for a 50 foot wide pass, would be about 33 ft/min. To achieve an RN_3 value of 0.06, with the motorized sweeper, and an entry time of 160 hours (6.7 days), about 21 hours of effort are required. This effort is equivalent to 2.5 cycles over the area at 5 mph. The 150r infinity planning dose without decontamination (see Figure 11.5) would require occupying a perfect shelter for about 6700 hours (280 days) at an $I_a(1)$ value of 2660 r/hr at 1 hour.

The difference in the RN_3 curves for each of the two methods, as shown in Figures 11.7 and 11.8, respectively, shows the strong influence of both the time-period of application and the level of the planning dose for the decontamination crews on the entry time, that is, the time when decontamination is completed and/or when permanent shelter exit can occur. For the short-time definition of the planning dose (see Figure 11.7), where earlier entry times are possible at the intermediate values of RN_3 than are possible for either higher or lower values, the influence of the two factors on the entry time is quite large. For the short-time definition, an optimum entry time and effectiveness occurs for each decontamination method. For the 75r exposure dose, as Figure 9.8 shows, t_e increases as RN_3 decreases at all values of t_e because the time-period for the 75r exposure dose of the decontamination crew(s) is not specified.

In the illustration, the decontamination methods and values of other parameters were selected and then the entry times were calculated. The reverse computation can also be made by selecting desired entry times first. The required RN_3 values are next determined. The decontamination effort required to achieve the RN_3 values is then calculated.

In any combination of selected variables, however, the lower limit of t_e will always be determined by the planning dose for the decontamination crews, and how the dose expenditure is scheduled by short-term exposures and by rotation of crews. In planning calculations, adjustment of the major parameters to appropriate values, as needed to obtain a desired solution of compatible values of RN_3 and t_e, usually provides means for realizing the desired solution.

Figure 11.8
CURVES FOR DETERMINING ENTRY TIME TO A DECONTAMINATED AREA AND REQUIRED VALUES OF RN_3 FOR DECONTAMINATION OF 10^6 SQ FT OF ASPHALT PAVEMENT BY MOTORIZED SWEEPING AND/OR FIREHOSING, WHERE $I_a(1)$ IS 2660 r/HR AT 1 HR, 35 MILES DOWNWIND FROM THE 1-MT YIELD SURFACE DETONATION WITH A WIND SPEED OF 15 MPH. THE DOSE LIMITS ARE 150 r FROM t_e TO 2.3 YEARS FOR THE SHELTER OCCUPANTS AND A TOTAL OF 75 r DURING THE DECONTAMINATION WORK FOR THE CREWS



CHAPTER 11 REFERENCES

1. Miller, C.F., A Theory of Formation of Fallout, USNRDL-TR-425 (1960).

2. The Radiological Recovery of Fixed Military Installation, NAVDOCKS TP-PL-13, revised (1958).

3. Lee, H., Estimating Cost and Effectiveness of Decontaminating Land Targets, USNRDL-TR-435 (1960).

Chapter 12

TARGET ANALYSIS PROCEDURES

12.1 The Target Complex Unit

A target complex is some real designated local area for which a radiological countermeasure system is to be designed. The target complex unit is a part of the target complex whose size is determined by the convenience of formulating plans for a set of integrated and self-contained countermeasure actions that can be carried out under local operational control. Thus, a target complex may be a city, a military base, or other large area; a target complex unit could be a factory, a city block or blocks, or some vital portion of a military base needed for carrying out the mission of that base.

A radiological analysis of the designated target complex units is made to develop data in the formulation of plans for countermeasure systems that consist of shelters for the emergency (transattack) phase and decontamination for the radiological recovery (postattack) phase. The analysis should provide information for. (1) designations of shelter locations for all people in the unit, and (2) plans for the recovery of target complex units.

The selection of target units for radiological analysis is made on the basis of the need of the resources in the unit for (1) continued sustenance of nearby survivors and (2) acceleration of the recovery of the nation, (see Chapter 7). Thus, if a particular target complex unit contains a utility plant. warehouses containing food and/or medicine, governmental offices, a factory. or other important facilities and receives sufficient fallout to make its operation hazardous to the operating personnel. decontamination of that complex unit may be assigned as a priority countermeasure action

Radiological analysis of target units, therefore, is specifically concerned with obtaining input information for determining what decontamination methods can be used or are needed, what entry times might be achieved for different levels of fallout, and what the schedule of actions should be to make the countermeasure system operate successfully.

12.2 The Role of Shelter in Radiological Countermeasure Systems

The role of the shelter in radiological countermeasure systems is discussed briefly here only to define, in a descriptive way, a shelter as a component of the system. Engineering details of shelters and shelter equipment are outside the scope of this discussion; they are discussed in other literature.

Conceptually, a description of the so-called "fallout" shelter is derived from the requirements for (1) human survival during the emergency phase during and after nuclear attack when the radiation levels from fallout are highest, and (2) radiological recovery in the postattack period.

The protective requirements for keeping the exposure dose to a low amount during the earlier times after attack have been specified in terms of the shielding residual number of shelters, RN_1. But, since the exposure dose from fallout accumulates with time, and because such doses may, in some locations, have high accumulations at rather long times after detonation, the shelter must be occupied continuously for an extended period of time after attack to achieve the computed (potential) RN_1 value of the shelter. Thus, a shelter, to provide protection from nuclear radiation, must be designed to accommodate people for time periods that may be counted in days, weeks, or months. Therefore, to assure a degree of survival in a shelter that is consistent with the protection from radiation exposure during this period, a number of shelter habitability requirements arise.

A shelter, to protect against the nuclear radiation from fallout, must have: (1) a specified capability for attenuating gamma rays defined by its shielding residual number and (2) a specified number of basic habitability features for human occupancy over an extended period of time. In other words, entry-ways and openings into a shelter must be designed to provide adequate shielding and to prevent the entry of fallout particles. For protection against only nuclear radiation, the structural part of the shelter need be no stronger than is needed to support the required shielding material.

The design characteristics of a shelter that provide protection against the thermal and blast phenomena (as well as against nuclear radiations) of nuclear detonations are (1) shielding, (2) adequate closure features, and (3) structural strength. For shelters located in the more densely populated areas where secondary thermal effects, large-scale fires, and possibly fire storms may occur, other design features may be important. As an example, a shelter designed to provide more than merely protection against nuclear radiation in such areas must have facilities for: (1) sealing the shelter from inside, (2) removing carbon dioxide, and (3) supplying oxygen or air for about 8 to 12 hours.

The basic habitability requirements of a shelter include: (1) ventilation, mainly for removal of body heat and moisture; (2) water, and food supplies, (3) hotel facilities, and (4) first aid supplies. The operational aspect of shelter habitability includes: (1) availability of large group shelters, (2) availability of shelter management and control procedures, and (3) availability of a postattack recovery plan and an organization capable of initiating social and economic recuperation within the target complex.

The radiological countermeasure system should provide group shelters for decontamination crews located, when possible, in or near the target complex unit so that crews have convenient access to the unit and to decontamination equipment. These group shelters should also have space for a monitoring crew, and should be provided with portable instruments, communication equipment to relay or obtain information for the preparation of recovery schedules (or for deciding which schedule to use if several alternate ones had been prepared), minimal equipment for personnel decontamination, and other needed supplies in addition to the normal shelter requirements. These group shelters should provide as high a level of protection against all effects of a detonation as is consistent with the survival of all the people (or the vital facilities) in the target complex unit itself.

Any existing structure that has, or is remodeled to have, the described protective and habitability features is considered a shelter as far as the countermeasure system is concerned. The same is true for specially built structures, whether they are shelters for small or large groups.

12.3 Description of Analysis Procedures

Since the major purpose of a radiological target analysis is to supply information for planning a radiological countermeasure system for a target complex unit, the analytical methods, as mentioned in Chapter 10, must consider the influence of both the radiation source geometries and the structural shielding on the ionization rates within the complex unit. Although a radiological target analysis provides data that is useful in specifying shelter requirements, only those used in planning recovery actions are discussed. The analytical methods given here are essentially those developed by Strope and Laurino[1] and by Lee[2] with some changes to generalize their application to a variety of target complex unit types.

One of the methods, called the point-location analysis, is designed to develop radiological information for specified locations in the target unit. The other method, called the unit-average analysis, is designed to develop radiological information applicable to the whole target complex unit. Many point-location analyses provide, in detail, the same information as the unit-average

analysis. Usually, some point-location analyses are actually required in making the unit-average analysis.

In both methods, exposure doses to persons in a specified area are estimated with respect to an assumed, or planned, countermeasure system. The mathematics of the methods of analyses, therefore, is designed to provide a means of estimating the over-all effectiveness of a proposed countermeasure system or of a component part of it. The analyses also identify which parts of the system might be either inadequate or superfluous.

As shown in Chapters 8 and 10, the decontamination effectiveness, in terms of the fraction of fallout remaining after decontamination, depends on the method used, the amount and type of fallout deposited, the effort applied during decontamination, and the type of surface. In turn, the feasibility of using a given method depends on the availability of the required equipment, supplies, and manpower. However, the detailed manner in which the method is applied depends on information from the target complex unit analysis in the form of a decontamination operations plan. In developing the plan, the target unit data that are gathered first include the various types of outside surfaces in the unit, their locations, and the total areas of each type of surface.

Most target units contain, in various configurations, several major types of exposed surfaces. When the surface types, surface configurations, and total area of each has been determined, appropriate combinations of different decontamination methods needed to recover the area can be established. Then, as the radiological analysis identifies which types of exposed surfaces predominates, either area-wise or with respect to the amount radiation that a surface contributes to a given location, further definition of possible method combinations can be made. The final selection of the procedures and schedules is based on: (1) the entry time achievable, (2) the amount of available equipment, supplies, and manpower; (3) the location of these resources; and (4) the state of organization and training of the available manpower.

The method of computing exposure doses in both methods of target analysis is discussed in Chapter 11. The dose accumulation over time is separated into three time periods: (1) the dose from time of fallout arrival to the decontamination starting time, (2) the dose during decontamination (i.e., radiological recovery), and (3) the dose after the decontamination process is completed. The second time period is eliminated for persons not involved in decontamination.

The potential exposure dose at a given location is calculated for two periods of time: (1) the dose from fallout arrival to fallout cessation and (2) the dose from fallout cessation to any later time. The feasibility of the countermeasure system is evaluated, in general, by use of Eq. 11.3. The measure of effectiveness

of the system is determined by the ratio of the exposure dose when the system is used to the potential exposure dose (i.e., the residual number); the most effective system has the lowest residual number.

In both the point-location and the unit-average method of computation, a detailed chart or map of the target complex unit is prepared. The chart shows all structures, streets, fences, paved and unpaved ground, trees and large shrubs, utility lines, and any other special features such as the location of shelters. From the chart, the types of exposed surfaces and the gross area of each surface are tabulated.

12.4 Methods for Estimating Relative Ionization Rate Contributions

In the point-location analysis, where interest is focused on the radiation at a few locations, estimates of the relative contribution of radioactive sources on nearby surfaces to the radiation at each location are made using the inverse square law (without including build-up factors). With the inverse square law, the analytical computations are easily and quickly carried out and, in most cases, provide sufficiently accurate information for preparing decontamination plans and schedules. If more accurate information on the nuclear radiation entering important structures is desired, computational methods such as given in the OCDM National Plan Appendix Series[3, 4] or described by Donovan and Chilton[5] can be used.

The inverse square law for a plane circular radioactive source area, neglecting the variation of the air attenuation with distance, is given by

$$I_j = \bar{I}_o \int_0^{\theta} \int_{r_1}^{r_2} \frac{d\theta r dr}{h^2 + r^2} \qquad (12.1)$$

where I_j is the unattenuated intensity, or ionization rate, from the sources on surface j as observed at the height, h, over the center of the area; I_o is the intensity at the contributing surface and is proportional to the intensity emitted per unit area of the surface; r_1 is the distance to the near edge of surface j; r_2 is the distances to the far edge of surface j; and θ is the angle subtended by the sector width of the area of surface j. The standard procedure, for an extended open area covered uniformly with fallout, is to use 3 feet for the value of h as the reference height for whole-body exposure to gamma radiation. It is also usual practice to assume I_o to be the same for all surfaces within the circular area.

Data from Operation Plumbbob,[6] obtained with a directional probe, show that the intensity contribution from sources more than 300 feet from the probe

at a height of 3 feet is negligible for an open land surface with some shallow gullies and sage brush cover. For the open-field type of contaminated area, the integral of Eq. 12.1, for h equal to 3 feet and for a radius of 300 feet, is then

$$I_\infty = 28.9\ I_o \tag{12.2}$$

Equation 12.2 is used as the open field or infinite field air-attenuated ionization rate for a uniform distribution of radioactive sources (i.e., fallout particles) over the area. It may be noted that attenuation due to both an average surface roughness and an average thickness of air is included in the intensity value of $28.9\ I_o$.

When material more dense than air intervenes between the surface area j within the area of circle with a 300-foot radius and a detector at its center, the right side of Eq. 12.1 is multiplied by an attenuation factor, A_j, for the material interposed between the jth surface and the detector. The evaluation of Eq. 12.1 for each surface out to a distance of 300 feet, assuming I_o to be the same for all surfaces, is used to define a contribution factor, $(cf)_j$, for each surface considered which is given by

$$(cf)_j = \frac{I_j}{\Sigma_j I_j} = \frac{I_o A_j f_j(\theta, r)}{I} \tag{12.3}$$

where $f_j(\theta,r)$ is the integrand of Eq. 12.1 and I is the sum of the I_j contributions.

If the various surfaces are decontaminated and the fraction of radiation contributed by the jth surface after decontamination is F_j of the fraction it originally contributed, then the fraction of the initial ionization rate remaining at the location of interest is

$$RN_3 = \Sigma_j F_j (cf)_j \tag{12.4}$$

Equation 12.4 is applicable only to the case where the radionuclides are not fractionated during the decontamination process. Also, the value of RN_3 in Eq. 12.4 applies only to the location for which it is evaluated.

The average, or effective, shielding attenuation factor for the location of interest, $\overline{A}_J$, is defined by

$$\overline{A}_J = \frac{\Sigma_j A_j f_j(\theta, r)}{28.9} \tag{12.5}$$

in which $\overline{A}_J$ is evaluated relative to the open-field ionization rate (i.e., at 3 feet above an extended contaminated area). The residual number, RN_3^o, for the location of interest, with respect to the open field ionization rate after decontamination, is therefore given by

$$RN_3^o = \overline{A}_J RN_3 \tag{12.6}$$

Thus when the intensity is expressed as an open-field ionization rate (as it is in the fallout model scaling system), the shelter stay times or entry times, and other countermeasure effectiveness requirements are computed by use of RN_3^o. However, when the intensity is determined from ionization rate measurements at the location of interest in the target complex unit, the operational data are calculated by use of RN_3 of Eq. 12.4. Monitoring data give the quantity I rather than I_∞.

In the unit-average analysis, the estimate of RN_3 might include consideration of the fraction of a day's time spent in an area where the average fraction of radiation remaining after decontamination is $\overline{F}_j$, or,

$$RN_3 = \Sigma_j \tau_j A_j \overline{F}_j \tag{12.7}$$

in which τ_j is the fraction of the time spent in the area j, A_j is the average shielding attenuation factor for the area, and $\overline{F}_j$ is the average fraction of radiation remaining on nearby contributing outside surfaces.

The value of $\overline{F}_j$ is estimated from a sum of the individual surface $\overline{F}_j$ values multiplied by the fraction of the total area decontaminated that consists of the jth type of surface. If individual persons' movements are known, Eq. 12.7 can be used to estimate an RN_3 value for these people. In some cases it is convenient to simplify the solution for RN_3 further; this is done, in Reference 1, by finding a controlling RN_3^*, defined as

$$RN_3^* = F_j(\max) \tag{12.8}$$

In this case, all estimates of entry times and decontamination starting times are based on the most difficult surface to decontaminate. While this method results in more pessimistic estimates of the operational parameters than the other methods, it is by far the simplest one to use computationally.

12.5 Analysis of a Simple Residential Area Target Complex Unit

To illustrate the use of the target analysis methods, especially the point-location method, a minimum sized idealized target complex unit is analyzed here. A minimum-sized target complex unit consists of all buildings and areas within a distance of about 300 feet from the center of the location of interest. If an area, rather than a single location is considered, the perimeter of the target complex unit is 300 feet away from the perimeter of the central area.

In the illustrative analysis, the following area dimensions and characteristics are assumed:

1. The target complex unit consists of residence lots and streets. It is 1 block long and 1-1/2 blocks wide. It includes two 50-foot wide streets and two 12-foot wide alleys lengthwise. One of the two streets is on the edge of the unit. One 50-foot wide cross-street is at one end of the unit. The outside dimensions of the unit are 708 by 556 feet.

2. Each lot is 50-feet wide and 150-feet deep. There are 13 lots the length of the block, or 39 in the target unit.

3. The houses, each 25 by 50 feet, are light wood frame structures, including garages, and are set back 30 feet from the street. The narrow side of each house faces the street; the longer side is 12-1/2 feet from the side of the lot.

4. The roofs of the houses are essentially flat, made of tar and gravel, and are at a height of about 15 feet from ground level.

5. Sidewalks along the street are 4 feet wide.

6. The driveways and walks from the street to each house have an area of 17 by 26 feet.

7. The front and side yards consist of lawns, flower beds, and small shrubs; the back yards are fenced and contain mostly plantings of flowers, lawns, shrubs, and trees.

In the illustrated analysis, three locations of interest were selected initially for treatment. These are: (1) a location at 3 feet above the center of the first floor of the house nearest the center of the target unit, (2) a location 3 feet above the roof of that central house, and (3) a location 3 feet above the center-line of the street directly in front of that central house. The latter two locations were selected mainly for purposes of estimating decontamination crew doses.

The calculated I_j/I_o values for the first floor of the central house location are summarized in Table 12.1. The attenuation factors for several materials are given in Figure 12.1[7] as a function of thickness; the values were calculated from linear absorption coefficients for a 0.5 Mev gamma energy. The selection of the 0.5 Mev average gamma energy was based on the calculated average fission-product photon energy (partially scattered) for times after detonation of several hours.[8]

The assumed average wood thickness was 2 inches for both the roofs and house walls. Since the roofs are flat, the radiation from the roofs of the adjacent houses is attenuated by 6 inches of wood and there are 4 inches of additional wood thickness for each house farther away. The radiation source, G_o, from the adjacent lawn and yard is represented by a circular area whose radius increases from the central house to the next nearest houses. The contributions from house roofs across the street and across the alley are included in the "front yards and street" and the "back yards", respectively, to simplify the summary; less than 0.1 in the value of I_j/I_o is involved in their contribution. The over-all shielding, or average attenuation factor, $\bar{A}_J$, for the center of the house, is 0.50 with respect to the open field reference intensity (i.e., without the houses in place).

The calculated I_j/I_o values for the location 3 feet above the roof of the central house are summarized in Table 12.2. The differences in Tables 12.1 and 12.2 are mainly due to differences in h and A_j for the two locations.

The calculated I_j/I_o values for the location 3 feet above the center-line of the street in front of the central house are summarized in Table 12.3. The fractional contribution of the radiation from sources on the street, sidewalks, front lawns, and driveways at the street center is computed from

$$I_j/I_o = 4 \int_o^{L/2} \int_o^{W/2} \frac{dxdy}{h^2+x^2+y^2} \qquad (12.9)$$

where L is the length of the rectangle in the x direction and W is the width in the y direction. The value of I_j/I_o is obtained from a graphical integration of

$$I_j/I_o = 4 \int_o^{L/2} \frac{1}{\sqrt{h^2+x^2}} \tan^{-1} \frac{W/2}{\sqrt{h^2+x^2}} \, dx \qquad (12.10)$$

Figure 12.1
ATTENUATION FACTORS OF SEVERAL MATERIALS FOR A PHOTON SOURCE ENERGY OF 0.5 Mev BASED ON LINEAR ABSORPTION COEFFICIENTS

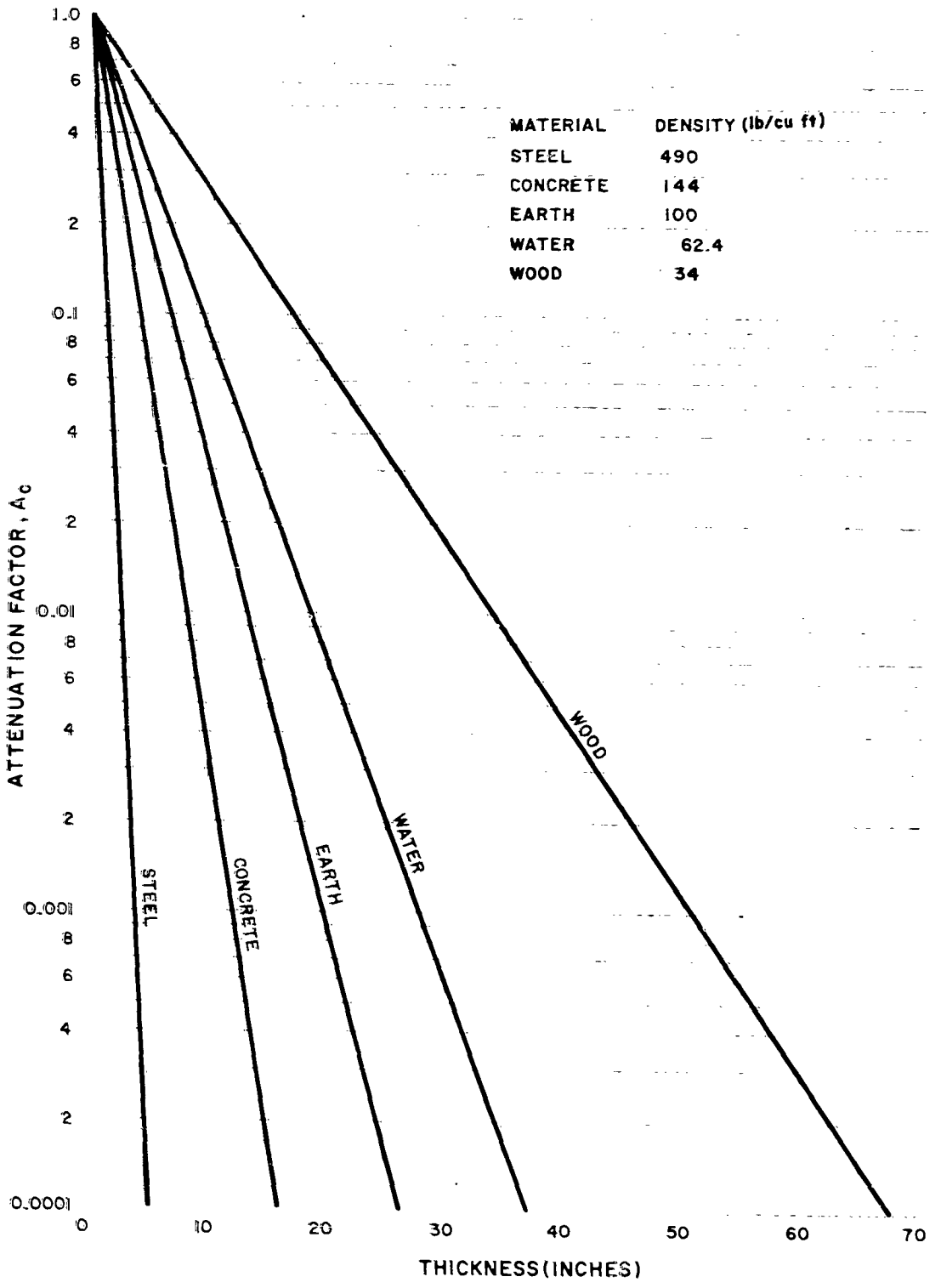


Table 12.1

ESTIMATED RELATIVE CONTRIBUTION OF VARIOUS SURFACE SOURCES TO THE RADIATION AT THE CENTER OF A LIGHT FRAME HOUSE

Surface Type	r_1(ft)	r_2(ft)	$\Delta\Theta/2$(rad)	h(ft)	Wood Thickness (in)	A_j	I_j/I_o	$\Sigma_j I_j/I_o$
Central House Roof	0	20	3.14	12	2	0.76	3.173	
Roofs (2) 1[a]	37.5	62.5	0.464	12	6	0.44	0.392	
Roofs (2) 2	87.5	112.5	0.244	12	10	0.26	0.063	
Roofs (2) 3	137.5	162.5	0.166	12	14	0.15	0.016	
Roofs (2) 4	187.5	212.5	0.124	12	18	0.087	0.005	
Roofs (2) 5	237.5	262.5	0.099	12	22	0.050	0.002	
Roofs (2) 6	287.5	312.5	0.084	12	26	0.029	0.001	3.652
Lawn & Yard, (G_o)	20	37.5	3.14	3	2	0.76	2.964	2.964
Side Yard 1-2	62.5	87.5	0.244	3	6	0.44	0.145	
Side Yard 2-3	112.5	137.5	0.166	3	10	0.26	0.035	
Side Yard 3-4	162.5	187.5	0.124	3	14	0.15	0.011	
Side Yard 4-5	212.5	237.5	0.099	3	18	0.087	0.004	
Side Yard 5-6	262.5	287.5	0.084	3	22	0.050	0.001	0.196
Back Yards(s) 1	37.5	300	1.106	3	2	0.76	3.493	
Back Yards(s) 2	62.5	300	0.220	3	6	0.44	0.304	
Back Yards(s) 3	113.5	300	0.078	3	10	0.26	0.040	
Back Yards(s) 4	162.5	300	0.042	3	14	0.15	0.008	
Back Yards(s) 5	212.5	300	0.025	3	18	0.087	0.002	
Back Yards(s) 6	262.5	300	0.016	3	22	0.050	0.001	3.848
Front Yards & Street	(same as back yards)						3.848	3.848
$\overline{A}_j$ = 14.508/28.9 = 0.50							SUM	14.508

a. Number of house from the central house, along the street

Table 12.2

ESTIMATED RELATIVE CONTRIBUTIONS OF VARIOUS SURFACE SOURCES TO THE RADIATION AT THE CENTER OF THE ROOF OF A LIGHT WOOD FRAME HOUSE

Surface Type	r_1(ft)	r_2 (ft)	$\Delta\theta/2$(rad)	h(ft)	Wood Thickness (in)	A_j	I_j/I_o	$\Sigma I_j/I_o$
Central House Roof	0	20	3.14	3	0	1.0	4.755	
Roofs (2)[a] 1	37.5	62.5	0.464	3	0	1.0	0.944	
Roofs (2) 2	87.5	112.5	0.244	3	0	1.0	0.245	
Roofs (2) 3	137.5	162.5	0.166	3	0	1.0	0.111	
Roofs (2) 4	187.5	212.5	0.124	3	0	1.0	0.055	
Roofs (2) 5	237.5	262.5	0.099	3	0	1.0	0.040	
Roofs (2) 6	287.5	312.5	0.084	3	0	1.0	0.028	6.178
Lawn and Yard (G_o)	20	37.5	3.14	18	4	0.58	1.589	1.589
Side Yard 1-2	62.5	87.5	0.244	18	4	0.58	0.331	
Side Yard 2-3	112.5	137.5	0.166	18	8	0.34	0.045	
Side Yard 3-4	162.5	187.5	0.124	18	12	0.20	0.014	
Side Yard 4-5	212.5	237.5	0.099	18	16	0.11	0.005	
Side Yard 5-6	262.5	287.5	0.084	18	20	0.066	0.002	0.397
Back Yard(s)	37.5	300	1.106	18	0	1.0	4.376	
Back Yard(s)	62.5	300	0.220	18	5	0.51	0.343	
Back Yard(s)	112.5	300	0.078	18	10	0.26	0.039	
Back Yard(s)	162.5	300	0.042	18	15	0.13	0.006	
Back Yard(s)	212.5	300	0.025	18	20	0.066	0.001	
Back Yard(s)	262.5	300	0.016	18	25	0.033	-	4.765
Front Yards and Street	(same as back yards)			-	-	-	4.765	4.765
							SUM	17.694

$\overline{A_j} = 17.694/28.9 = 0.61$

a. One roof on each side of middle house

Table 12.3

ESTIMATED RELATIVE CONTRIBUTION OF VARIOUS SURFACE SOURCES TO THE RADIATION AT THE CENTER OF A STREET

Surface Type	Area (sq ft)	r_c(ft)	h(ft)	Wood Thickness (in)	A_j	I_j/I_o	$\Sigma I_j/I_o$
Street	58x600	-	3	0	1.0	17.71	
Street and Front Yard	110x600	-	3	0	1.0	21.52	21.52
Roofs: Two nearest Houses	25x50	80	12	4	0.58	0.222	
Roofs: 1 (4)	25x50	94.4	12	4	0.58	0.321	
Roofs: 2 (4)	25x50	128	12	5	0.51	0.155	
Roofs: 3 (4)	25x50	170	12	5	0.51	0.090	
Roofs: 4 (4)	25x50	215	12	6	0.44	0.048	
Roofs: 5 (4)	25x50	262	12	6	0.44	0.031	
Roofs: 6 (4)	25x50	310	12	6	0.44	0.023	0.890
Side Yards 0-1 (4)	25x50	83.8	3	~1	0.9	0.640	
Side Yards 1-2 (4)	25x50	109.5	3	2	0.8	0.332	
Side Yards 2-3 (4)	25x50	148.5	3	3	0.7	0.040	
Side Yards 3-4 (4)	25x50	192.5	3	4	0.6	0.020	
Side Yards 4-5 (4)	25x50	239	3	5	0.5	0.011	
Side Yards 5-6 (4)	25x50	286	3	6	0.4	0.006	1.049
Lot Areas, Nearest (2)	50x50	80	3	0	1.0	0.780	
Front to Rear 1 (4)	50x50	94.4	3	0	1.0	1.124	
of Houses 2 (4)	50x50	128	3	0	1.0	0.608	
3 (4)	50x50	170	3	0	1.0	0.344	
4 (4)	50x50	215	3	0	1.0	0.216	
5 (4)	50x50	262	3	0	1.0	0.144	
6 (4)	50x50	310	3	0	1.0	0.104	(3.320)*
Back Yards*				--	0.4	--	1.62
						SUM	25.12

* $\Sigma_j I_j/I_o = (28.9\text{-}21.52\text{-}3.32)A_j$

$\overline{A}_j = 25.12/28.9 = 0.87$

The sums for W/2 values of 55 and 29 (h=3) at several L/2 values are given in Table 12.4. The intensity contribution from sources on the roofs and side yards are computed by assuming that all the sources on the area are concentrated at the center of the respective sub-areas. The point source strength is then I_o x Area; the inverse square law for this source geometry is

$$I_j / I_o = \frac{\text{Area} \times A_j}{h^2 + r_c^2} \tag{12.11}$$

where r_c is the distance to the center of the contributing source area. The contributions of sources on the lot areas without the houses is computed so that the contribution of the sources on the back yards (and the more distant roofs, etc.) is determined by difference from the open field reference intensity of $28.9 I_o$.

A summary of the relative radiation contribution factors, by surface type, for the three selected locations is given in Table 12.5. The intensity contributions of the sources on the streets and sidewalks for the house locations is computed from

$$I_j / I_o = 2Aj \int_o^{\theta} d\theta \int_{L_1/\cos\theta}^{L_2/\cos\theta} \frac{r\,dr}{h^2 + r^2} \tag{12.12}$$

or

$$I_j / I_o = 2.303Aj \int_o^{\theta} \log \frac{(h^2 \cos^2\theta + L_2^2)}{(h^2 \cos^2\theta + L_1^2)}\, d\theta \tag{12.13}$$

For small values of L_1 and L_2 and/or large values of h, Eq. 12.13 is integrated graphically; however, for small values of h and large values of L_1 and L_2, the $h^2 \cos^2_\theta$ term is negligible. This is the case here where L_1 is 51 feet and L_2 is 109 feet (from the center of the to the near and the far sidewalk, respectively. Thus the street and sidewalk source contributions to the intensity at the center of the house are given by

$$I_j / I_o = 1.52\ \Sigma_j\ A_j \Delta\theta_j / 2 \tag{12.14}$$

The A_j and $\Delta\theta_j/2$ are the same as those of Table 12.1 for the back yard source contributions; the value of I_j/I_o for the center of the house is 1.47. For the roof location, the multiplier to the right side of Eq. 12.14 is 1.45 and I_j/I_o is 1.40.

Table 12.4

INVERSE SQUARE LAW VALUES OF I_j/I_o FOR THE CENTER OF RECTANGULAR SOURCE AREAS
(h=3 ft, A_j=1.0)

L/2	W/2=55ft	W/2=29ft
10	10.95	10.14
20	14.46	13.08
40	17.46	15.28
100	20.12	16.88
300	21.52	17.71

The driveway source contributions, assuming the driveway to be at one side of the house, are 442 $\Sigma_j A_j/r_c^2$, which, for the 12 driveways nearest the central house sums to 0.48 for the inside center location and to 0.37 for the roof location. At both of the central house locations, the sources on lawns and on the yards are the largest contributors to the intensity; at the street center-line location, the sources on the street, sidewalks, and driveways together contribute 75 percent of the total intensity.

Sartor and Owen[9] report some data comparing the contribution factors computed from the inverse square law with measurements that were made during the contamination of about 3 acres of land, including buildings, at Camp Parks, California. In these experiments, different surface areas were contaminated serially with sand particles tagged with Ba(La)-140 and ionization-rate measurements were made at several selected locations after the contamination of each different area or building roof. The differences in the successively measured ionization rates, I_j, after each contamination step, at each of two locations, are plotted against the calculated and normalized contribution factors in Figure 12.2.

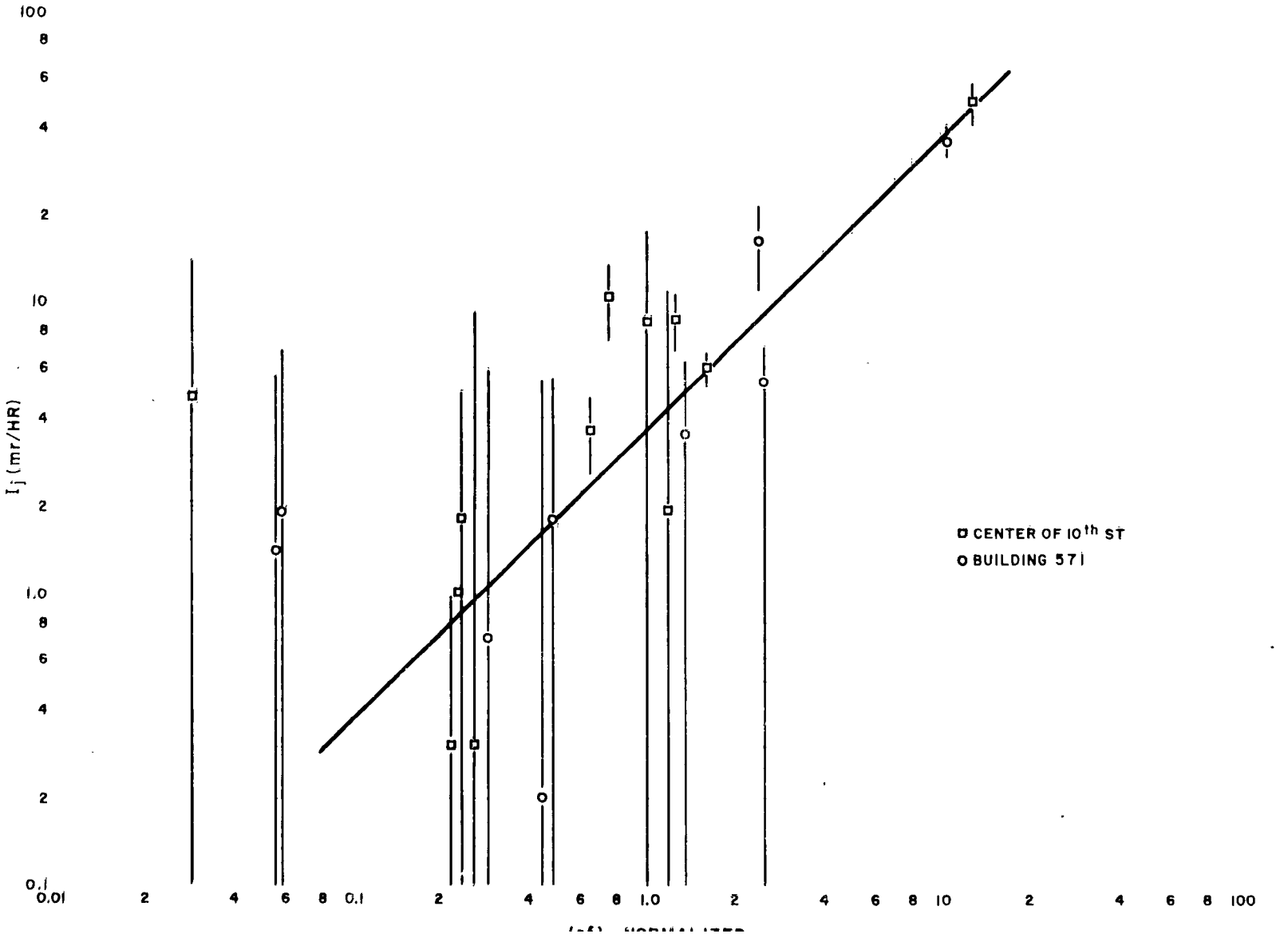
The length of the "error" line for I_j, as determined from the differences in increasingly larger measured ionization rates, was calculated by assuming that the error of each measurement was 10 percent of the measured value. The fact that several of the data points with relatively small error lines lie to the left of the line of unit slope indicates that the estimated shielding attenuation factors are too low. The deviations of the points from the line of unit slope do not correlate with distance as would be expected if large errors were introduced in the calculations using the inverse square law excluding the term for the variation of the air attenuation with distance. The data do

Table 12.5

SUMMARY OF THE RELATIVE INTENSITY AND CONTRIBUTION FACTORS AT SELECTED LOCATIONS, BY SURFACE TYPE

Surface Type	I_j/I_o	$(cf)_j$
1. Inside Center House		
Roofs, Tar and Gravel	3.65	0.25
Streets, Sidewalks, and Driveways	1.95	0.14
Lawns and Yards	8.91	0.61
2. Top of Roof of Center House		
Roofs, Tar and Gravel	6.18	0.35
Streets, Sidewalks, and Driveways	1.77	0.10
Lawns and Yards	9.74	0.55
3. Street Center at Center House		
Roofs, Tar and Gravel	0.89	0.04
Streets, Sidewalks, and Driveways	18.98	0.75
Front Lawns	2.54	0.10
Back and Side Yards	2.71	0.11

Figure 12.2
MEASURED VALUES OF I_j COMPARED WITH NORMALIZED VALUES OF THE CONTRIBUTION FACTORS COMPUTED FOR A BUILDING AND STREET LOCATION AT CAMP PARKS, CALIFORNIA, DURING THE COMPLEX II EXPERIMENT.[8] THE CONTRIBUTION FACTORS ARE CALCULATED BY USE OF THE INVERSE SQUARE LAW AND ESTIMATED SHIELDING ATTENUATION FACTORS FOR INTERVENING STRUCTURES



indicate that the use of the inverse square law is satisfactory for determining, or identifying, the important contributing source areas and for estimating the relative importance of the sources on each of the areas that contribute a significant fraction of the total radiation at a location.

The gross areas of each surface type in the assumed residential target complex unit are summarized as follows:

1.	Asphalt and Concrete:		
	Streets and Sidewalks (58x556 + 112x650)	:	105,048 sq ft
	Alley ways (2x12x650)	:	15,600 sq ft
	Driveways and Walks (39x26x17)	:	17,238 sq ft
	Total	:	137,886 sq ft
2.	Tar and Gravel Roofs (39x50x25)	:	48,750 sq ft
3.	Lawns and Yards		
	Back Yards (39x50x64)	:	124,800 sq ft
	Side Yards (39x25x50)	:	48,750 sq ft
	Front Yards (39x26x33)	:	33,462 sq ft
	Total	:	207,012 sq ft
	All Surfaces	:	393,648 sq ft

The relative contribution factors for the source areas contributing to the intensity at the selected locations, and the area(s) of each surface type, together provide the information needed to describe the character of the target unit with regard to its interaction with radiation sources on the various surface areas. The next step is to investigate what changes in ionization rates occur when the source strengths on the various surfaces are altered by decontamination processes.

12.6 Decontamination Analysis of The Assumed Residential Area Target Complex Unit

The decontamination analysis of a target complex unit consists of the following determinations:

1. Selection of decontamination methods applicable to the surface types and their configuration in the target unit

2. Entry times that are possible considering the over-all decontamination effectiveness of the different combinations of methods

3. Alternate schedules for use of the methods and estimates of the exposure dose of crew members in carrying out each schedule

4. Decontamination starting times for several assumed levels of fallout

5. Selection of probable entry times based on the time required to decontaminate the exposed surfaces in the target complex unit

6. Specification of the manpower, equipment, and supplies needed to carry out the various plans and schedules

An initial plan or schedule of the decontamination procedures can be devised and the potential effectiveness of the plan can be determined without reference to on-hand items required for its implementation. This initial plan would provide useful guidance in selecting needed items of equipment and in establishing, as an objective goal, an adequate organization and training program for carrying out the plan. A current realistic plan, however, should be devised and kept up-to-date on the basis of available on-hand items and organizational capabilities.

Methods for making some of the above determinations are illustrated below for the residential target complex unit located at the 2000 r/hr at 1 hr level 35 miles downwind from a 1-MT yield surface detonation. The assumed countermeasure system includes adequate shelter for the residents of the unit since without their survival of the occupants no decontamination plan could be carried out. Some of the possible decontamination method-surface combinations, possible levels of expended effort, the effectiveness of the methods, working times, and crew sizes are given in Table 12.6.

The values of E and F for firehosing and motorized sweeping the paved areas are taken from Table 11.3. The two levels of effort for firehosing refer to a factor of two change in the forward speed of the crews; the two levels of effort for street sweeping refer to 1 and 2 passes over the area at a constant speed of 5 mph.

The effort and effectiveness for firehosing the tar and gravel roofs are estimated from

$$M* = 0.0038\ y^{0.74} \qquad (12.15)$$

where y is 9.4 + 450 or about 460 gm/sq ft (assuming about 1 lb of gravel/sq ft on the roof); hence

$$F = 0.038 + 49\ \exp(-0.766E^{1/3}) \qquad (12.16)$$

The remainder of the data are taken from Tables 10.4 and 10.5.

The hand stripping of the lawns and yards with shovels and wheel barrows would take a crew of 4 about 21.5 days working 8 hours a day. If 10 crews of 4 men each were available, the time required is about 2.2 days. The removal of 2 inches of top soil from the yards and lawns would involve hauling away or otherwise disposing of about 1280 cubic yards of soil. For removing the top layer of soil, the tractor scraping and bulldozing are the most efficient of the methods listed in Table 12.6. The rather high effort for sod cutting and removal is due to the picking up of the sod and hauling it away by wheel barrow. If the sod were loaded directly and hauled away as fast as it was cut by the same crew of 7, the effort would be reduced to about 320 man-minute per 10^4 sq ft; this effort corresponds to a working rate of about 220 sq ft/minute.

The calculated residual numbers for the three reference locations in the residential target complex unit and the earliest times of occupancy (of the reference locations) or entry times, based on these residual numbers, are given in Table 12.7. The most effective combination of decontamination methods give RN_3 values of 0.04 and 0.06; the least effective give RN_3 values between 0.1 and 0.2. The calculated RN_3^o values include weighting factors based on the shielding attenuation factors for the assumed geometry of the target unit.

The calculated entry times based on the more liberal planning dose for all locations is from less than 1 day to 5.5 days after detonation as read from Figure 11.4 (note that $RN_3^o I_a(1) = I_a(I)$ of Figure 11.4). Without decontamination, the same planning dose would give entry times of 11, 18, and 40 days after detonation, respectively, for the central house, the top of its roof, and the street center. Thus the effect of the target complex geometry and shielding is to

Table 12.6

SUMMARY OF METHOD-SURFACE COMBINATIONS, WORKING RATE, THE EXPECTED EFFECTIVENESS, WORKING TIME, AND CREW SIZE FOR DECONTAMINATING THE RESIDENTIAL AREA TARGET COMPLEX UNIT WHERE I(1) = 2000 r/hr at 1 hr, y = 9.4 gm/sq ft

Method-Surface Combination	Rate (sq ft/min)	F	Working Time (hrs)	Crew Size (no. men)
1. Firehose Streets, Sidewalks, and Driveways	3500	0.062	0.8	5 (2 nozzles)
	1250	0.043	1.6	5 (2 nozzles)
2. Sweep Streets, Sidewalks, Driveways and Alleys	2000	0.24	1.2	1 (1 pass)
	1000	0.080	2.3	1 (2 passes)
3. Firehose Tar and Gravel Roofs	100	0.11	8.1	6 (2 nozzles)
4. Hand Stripping Lawns and Yards	20	0.1	172	4
5. Tractor-Scraping Lawns and Yards	70	0.1	49	2
6. Bulldozing Back Yards	90	0.05[a]	23	1
7. Sod Cutting and Lawn Removal	35	0.02	28[b]	7

a. Estimated.

b. For front yards and half the area of the side yards.

Table 12.7

MINIMUM AND MAXIMUM RESIDUAL NUMBERS, AND ENTRY TIMES BASED ON THESE RESIDUAL NUMBERS; FOR THE RESIDENTIAL TARGET COMPLEX UNIT, ASSUMING I(1) = 2000 r/hr at 1 hour, y = 9.4 gm/sq ft

Surface Type of Contributing Sources	Central House Center		Central House Roof Top		Street Center	
	min.	max.	min.	max.	min.	max.
1. Final Residual Number: $(cf)_j F_j$						
Roofs	0.028(3)*	0.028(3)	0.038(3)	0.038(3)	0.004(3)	0.004(3)
Paved Areas	0.006(1)	0.034(2)	0.004(1)	0.024(2)	0.032(1)	0.180(2)
Lawns	0.005(7)[a]	0.024(4)[a]	0.005(7)[b]	0.023(4)[b]	0.002(7)	0.010(4)
Yards	0.018(6)[c]	0.037(4)[c]	0.016(6)[d]	0.033(4)[d]	0.006(6)	0.011(4)
RN_3	0.057	0.123	0.063	0.118	0.044	0.205
RN_3^0	0.028	0.062	0.038	0.072	0.038	0.178
2. Entry Time Based on RN_3^0: t_e (hours after detonation)						
Planning Dose						
30r/day or 1000r/yr	21	51	30	60	30	132
150r after t_e	18	170	46	250	46	1770

a. $(cf)_j = (2.964/2 + 0.196/2 + 3.848 - 1.95)/14.51 = 0.24$; Lawn area = 1/2 of side yards plus front yards less paved areas.

b. $(cf)_j = (1.589/2 + 0.397/2 + 4.765 - 1.77)/17.69 = 0.23$

c. $(cf)_j = (3.848 + 2.964/2 + 0.196/2)/14.51 = 0.37$; Yard area = back yards plus 1/2 of side yards.

d. $(cf)_j = (4.765 + 1.589/2 + 0.397/2)/17.69 = 0.33$

* Method number, from Table 12.6, is given in parentheses.

reduce the entry time from 52 days, or by about 41 days, for the central house location. On the basis of decontamination effectiveness only, decontamination of the complex unit would permit occupancy of the central house at the end of the first day. This is true even for the planning dose of 150$_r$ from t_e to infinity time (where t_e is taken from Figure 11.5).

The recovery plan for the target complex unit assumes the availability of one motorized sweeper, and/or equipment for firehosing the streets and roofs, one bulldozer for scraping the backyards; and shovel and wheel barrow crews for removing the lawns and top soil from the side yards. In the first estimate of the doses to the various crew members, the decontamination methods will be assumed to be employed serially in the order given; later, the sequence is adjusted to a tighter schedule including minor corrections, if needed, to the estimates of the crew dose.

The reasons for deciding to decontaminate the paved areas first with the sweeper (or by firehosing) are: first, these areas can be cleaned rapidly by either of the two methods, second the paved areas are about 35 percent of the area so that a rather substantial fraction of the fallout is removed rapidly, and third, the clean paved areas can be used to work from, in carrying out the remainder of the recovery procedures.

The exposure dose to the crews in carrying out the procedures is next calculated through estimates of the decontamination crew residual numbers, RN_2.

The exposure dose to the street sweeper operator during decontamination consists of intensity contributions from radioactive sources on the street being cleaned; on all other nearby surfaces and in the hopper which collects the fallout particles as the sweeping progresses The ionization rate from the sources in the hopper increases until the operator stops sweeping; it then remains constant during the time of haul to a dumping area, and decreases to zero when the hopper is emptied.

At 5 mph (440 ft/min) the sweeper could make a round trip on the street 650 feet long in about 3 minutes. In this time, picking up 76 percent of the 9.4 grams of fallout per sq ft, the hopper collects about 94 pounds of fallout particles (plus other dirt). By dumping the material in the alleys (or near a street corner in a prepared pit), the average hauling time should be about one minute and, for return to sweeping another minute, the gross operational rate is then about 5 minutes per round trip. Thus the first pass on the streets, neglecting the alley ways, would take (5 3) x 61 or 102 minutes (20 round trips) If the same amount of material per round trip is collected in the second pass over the area as was collected on the first pass and an additional 16 percent of

the particles are removed, then about 14 minutes could be spent sweeping before dumping. However, to limit the exposure dose from the hopper source, a sweeping time per trip of 10 minutes is taken; the second sweeping pass then takes (12/10)x61 or 73 minutes (6 round trips). The total time for the two passes is 175 minutes, or approximately 3 hours.

The reference location for estimating RN_2 for the sweeper operator is the center-line of the street in front of the central house. In estimating the exposure dose of the operator from the surrounding source areas and sources on the streets, it is assumed that the contribution from the street sources decreases linearly with time for each pass. The same result is obtained if each section of the various streets is considered separately.

The relative intensity contributions, at the sweeper operator's position (at the reference location), from the street and surrounding area sources for: (1) the start of sweeping, (2) the end of the first pass, and (3) the end of the second pass, from Tables 12.5 and 12.6, are:

$$I = 25.12 A_s I_o \qquad \text{at } t = 0 \tag{12.17}$$

$$\begin{aligned} I &= \left[6.14 + 0.24 \times 18.98\right] A_s I_o \\ &= 10.70 A_s I_o \qquad \text{at } t = 102 \text{ min} \end{aligned} \tag{12.18}$$

and

$$\begin{aligned} I &= \left[6.14 + 0.08 \times 18.98\right] A_s I_o \\ &= 7.66 A_s I_o \qquad \text{at } t = 175 \text{ min} \end{aligned} \tag{12.19}$$

where A_s is the shielding factor for the sweeper and t is the time. The ionization rate at the sweeper's operator's location during sweeping, from sources on all surrounding areas and streets is then given by

$$I' = A_s I_o (25.12 - 0.141t), \qquad t = 0 \text{ to } 102 \text{ min} \tag{12.20}$$

and

$$I' = A_s I_o (10.70 - 0.0416t), \quad t = 0(102) \text{ to } 73(175) \text{ min} \tag{12.21}$$

The ionization rate at the operator's location from sources in the hopper during sweeping, assuming a constant rate of pick-up, is estimated from

$$I_h = \frac{A_h V_{sw}(1-F_1)I_o t}{x_h^2} \qquad (12.22)$$

where A_h is the average attenuation factor due to the structural steel of the sweeper and self-shielding of the dirt in the hopper. V_{sw} is the sweeping speed. F_1 is the fraction of fallout remaining after the first pass, and x_h is distance between the operator and the hopper. The ionization rate at the operator's position during the haul to a dump is equal to I_h when t in Eq. 12.22 is the sweeping time for one round trip. For the second pass, $1-F_1$ is replaced by F_1-F_2 where F_2 is the fraction of fallout remaining after the second pass.

The over-all RN_2 value for the sweeper operator is estimated most easily by parts, neglecting radioactive decay. It can be calculated relative to a measured value of the ionization rate at a given location or to the reference open field ionization rate. The latter reference is used here because the whole calculation is based on an assumed open field standard intensity of 2000 r/hr at 1 hour.

For the open field reference intensity the potential exposure dose is $28.9 I_o t$; relative to the location at the center-line of the street, it is $25.12 I_o t$. The values of RN_2 for the sweeper operator, for the radiation from sources on the street and surrounding, is given by the ratio of the exposure doses obtained by integration of Eqs. 12.20 and 12.21 to the potential exposure dose. The RN_2 values are

$$RN_2'(1) = \frac{A_s(25.12 - 0.0705t)}{28.9}, \quad t = 102 \text{ min} \qquad (12.23)$$

and

$$RN_2'(2) = \frac{A_s(10.70 - 0.0208t)}{28.9}, \quad t = 73 \text{ min} \qquad (12.24)$$

where the prime on RN_2 indicates reference to the street and surrounding area sources and the number in parentheses is the pass number.

For a V_{sw} value of 2000 ft^2/min and a distance of 6 feet between hopper and operator, RN_2 values for the hopper source contributions during sweeping, as obtained from integration of Eq. 12.22, are

$$RN_2''' (1) = 0.730A_h t \quad , t = 3 \text{ min} \tag{12.25}$$

and

$$RN_2''' (2) = 0.154A_h t \quad , t = 10 \text{ min} \tag{12.26}$$

The RN_2 values for the haul to the dump are given by

$$RN_2''' (1) = 1.46A_h t \quad t = 3 \text{ min} \tag{12.27}$$

and

$$RN_2''' (2) = 0.308A_h t \quad , t = 10 \text{ min} \tag{12.28}$$

in which the RN_2''' values are independent of the time to haul to the dump.

Data from the Camp Parks Complex II experiments reported by Sartor and Owen[8] using the Wayne street sweeper are summarized in Table 12.8 with the values of A_s and A_h derived from that data; the values 0.67 and 0.37, respectively, are used in the subsequent calculations. It may be noted that the actual sweeping rates obtained in the experiment are about a factor of two less than the values used in Eq. 12.25 to 12.28. At the full rate in the Complex II experiments,it should have taken only 6 minutes to sweep Hamilton Avenue and 7 minutes to sweep 10th Street. The extra time shown resulted because the operator overlapped previously swept areas more than allowed for in the higher rate and wasted time in turning around on uncontaminated areas. The use of the higher rate here in the estimates of RN_2 for the sweeper operator due to the radiation from the sources in the hopper assumes a well-trained operator.

Table 12.8

ESTIMATED VALUES OF A_s, A_h, AND RN_2 (h), FROM WAYNE STREETSWEEPER DATA OF COMPLEX II EXPERIMENTS

	Hamilton Ave	10th Street
Area (sq ft)	12,050	13,970
Sweeping Time (min)	10	16
Rate (sq ft/min)	1,205	873
Time Hauling to Dump (min)	3	4.5
Time Return to Area (min)	3.5	3
Dose from Hopper During Haul (mr)	9	12
A_s	0.68	0.66
Dose from Surroundings During Sweeping (mr)	5.2	7.6
Total Dose Received (mr)	31.8	52.1
Dose During Sweeping (mr)	17.6	32.5
Exposure Dose During Sweeping (mr)	9.33	14.4
Ratio of Exposure Dose to Infinite Field Dose	0.81	0.78
Infinite Field Dose (mr)	11.5	18.4
$RN_2(h)$	1.53	1.77
A_h	0.367	0.366
Dose Rate from Hopper During Haul (mr/hr)	180	160
A_h (from dose rate equations)	0.386	0.316

Substitution of $A = 0.67$, $A_h = 0.37$, and the appropriate values of t in Eqs. 12.23 to 12.28 give the following RN_2 values:

$$RN_2' \quad (1) = 0.416$$

$$RN_2' \quad (2) = 0.213$$

$$RN_2'' \quad (1) = 0.810$$

$$RN_2'' \quad (2) = 0.570$$

$$RN_2''' \quad (1) = 1.62$$

$$RN_2''' \quad (2) = 1.14$$

The over-all RN_2 value for the two passes is the sum of the above RN_2 values each weighted by the fraction of the total time that the respective sources contribute to the operator's exposure dose. The fractions, in the order given, are: 102/175, 73/175, 61/175, 61/175, 20/175, 6/175. The sum, or over-all RN_2 value for the planned sweeping decontamination operation, therefore, is 1.05.

The order of the values of the individual primed RN_2's are, as might be expected, the largest contributions for the sources in the loaded hopper and the smallest for the most distance sources. The largest contributor to RN_2, however, is RN_2'' (1) even with only 3 minutes of sweeping time. Thus the two most important parameters that determine the over-all value of RN_2 are the time allocated to each round trip on the first pass and the time spent hauling the loaded hopper to the dumping location.

The value of RN_2 for firehosing the streets, driveways and sidewalks, as an alternative to the street sweeping procedure, is also calculated with respect to the center of the street in front of the central house. The RN_2 value for the firehosing crew members is estimated for the paved surfaces along one block in the target complex unit; the value for other similar areas is assumed to be the same.

The surface sources and crew actions during decontamination that contribute to the exposure dose of the firehosing crew members include: (1) the exposure dose from all surrounding sources while the crew is setting up the pump and connecting the hoses (in the illustration, the exposure dose during travel from shelter to a fire station or other storage area and to the site is neglected); (2) the exposure dose from the surrounding sources during decontamination of the paved areas including the decrease in ionization rate due to the removal of sources from the street during the firehosing process; and (3) the exposure dose from the fallout particles that are piled up in front of the nozzle teams by the washing process.

The firehosing procedure is started at one end (the highest) of the block and the fallout is flushed down the street (if it is sloped); the particles are flushed into a storm drain at the (lower) end of the block. Since the front nozzleman should receive the largest exposure dose during firehosing, the decontamination crew residual number is computed for that crew member.

The slower firehosing rate, 1250 sq ft/min, with an expected decontamination effectiveness of 0.043, is selected for the calculation. The area of the paved surfaces along one block is 46,300 sq ft; thus the flushing time is 37 minutes. As given in Table 12.9 (see later discussion), the setup time is 15 minutes, including moves to another hydrant location, and the time to roll up the hoses prior to moving to another location is assumed to be 20 minutes. These times are obviously dependent on the state of training of the crews and the locations involved in the various moves. The total time spent by the crews to decontaminate the street along one block is 72 minutes.

Assuming no shielding from equipment during setup, the value of RN_2 for the firehose crew members, relative to the street-center location, is

$$RN_2' = 25.12/28.9 = 0.869, \quad t = 15 \text{ min} \tag{12.30}$$

For a uniform forward speed down the street, the ionization rate from the sources on the street should decrease more or less linearly until about 300 feet of street are cleaned and then it should remain constant (providing other portions of the street in adjacent blocks are not cleaned simultaneously). From Table 12.5, the variation with decontamination time of the ionization rate contributions from the sources on surrounding areas is given by

$$I = 25.15I_o, \qquad t = 0 \tag{12.31}$$

$$\begin{aligned} I &= 6.14I_o + \left[(1+0.04)/2\right] \times 18.98I_o \\ &= 16.01I_o, \qquad t = 18.5 \text{ min} \end{aligned} \tag{12.32}$$

and

$$I = 16.01I_o, \qquad t = 18.5 \text{ to } 37 \text{ min} \tag{12.33}$$

Using the values of I at the indicated times gives, for the first 18.5 minutes of firehosing,

$$I = (25.12 - 0.492t)I_o \tag{12.34}$$

Hence, the RN_2 values for the first and second 18.5 minute periods of firehosing, for the surrounding and street sources, are

$$RN_2''(1) = 0.712, \qquad t = 18.5 \text{ min} \tag{12.35}$$

and

$$RN_2''(2) = 0.554, \qquad t = 18.5 \text{ min} \tag{12.36}$$

In estimating the intensity contribution from the sources in the fallout particles accumulating in front of the crew as they move down the street, each nozzle team is assumed to move from the center of the street to the sidewalk and back so that, on the average, the front nozzleman's position is at a location half the distance between the center of the street and the sidewalk. The accumulated fallout from the flushing is assumed to form a line source of unit width across the street and moves down the street with the same speed as that of the nozzle teams. The intensity of this source increases as the decontamination proceeds and as the particles piled up. Averaging in the particles removed from the driveways and walks, the intensity due to this line source at the front nozzleman's location, from the inverse square law, is

$$I = \frac{\text{Rate } (1-F)I_o \; f_L(d_s, x)t}{L} \tag{12.37}$$

where L is the length of the line source of unit width, and $f_L(d_s, x)$ is the contribution factor for the source geometry. The contribution factor is given by

$$f_L(d_s, x) = \int_0^x \frac{dx}{h^2 + d_s^2 + x^2} \tag{12.38}$$

where d_s is the perpendicular distance from the nozzleman to the line source and x is the distance along the line source from that perpendicular. For each nozzle position, d_s is taken as 25 feet, which is 5 feet beyond the point where

the water stream hits the pavement. In one direction x is 14.5 feet and in the other it is 43.5 feet. For these conditions, Eq. 12.38 is

$$f_L(d_s, x) = \frac{1}{25.2}\left[\tan^{-1}\frac{43.5}{25.2} + \tan^{-1}\frac{14.5}{25.2}\right] = 0.0622 \qquad (12.39)$$

With this value of $f_L(d_s, x)$, Eq. 12.37 is

$$I = 1.29\, I_o t\,, \qquad t = 37 \text{ min} \qquad (12.40)$$

and, for the contribution from the line source, the crew residual number is

$$RN_2''' = 0.824\,, \qquad t = 37 \text{ min} \qquad (12.41)$$

For roll up in the decontaminated street, the crew residual number is

$$RN_2''' = \frac{6.14+0.043\text{x}18.98}{28.9} = 0.241\,,\ t = 20 \text{ min} \qquad (12.42)$$

The over-all RN_2 value for the nozzle men is obtained, as before, by weighting each primed RN_2 value by the fraction of the total time that each respective operation contributes to the exposure dose. The respective weighted RN_2 values are (15/72)x0.869, (18.5/72)x0.712, (18.5/72)x0.554, (37/72)x0.824, and (20/72)x0.241; the sum is 0.996. The largest contributing source to RN_2 for the firehosing crew is from the fallout particles accumulating in front of the nozzle teams.

In firehosing the house roofs, the procedure is to clean two adjacent houses simultaneously. One nozzle crew of three men flushes the two roofs from front to rear (and to the side). For this procedure, the method for estimating RN_2 for the firehosing crews includes consideration of: (1) the exposure dose during set up of the pump and lay-out of the hoses onto the roofs prior to the start of flushing, and (2) the exposure dose from the roof sources and surrounding sources during flushing. In the computation, it is assumed that the streets have been cleaned by firehosing before the roof decontamination procedure is started and that the intensity contribution from the particles flushed off the roof is negligible.

Data pertinent to the estimation of RN_2'' values for firehosing tar and gravel (or other) roofs from Complex I and II experiments[9] are summarized in Table 12.9. If a linear decrease in the roof source contribution to the intensity during the flushing procedure is assumed, RN_2'' for a single pass, relative to the open field dose, is

$$RN_2''(1) = \frac{I_s + 1/2(1+F_1)I_R}{28.9I_o} \tag{12.43}$$

for the first pass,

$$RN_2''(2) = \frac{I_s + 1/2(F_1 + F_2)I_R}{28.9I_o} \tag{12.44}$$

for the second pass, and

$$RN_2''(3) = \frac{I_s + 1/2(F_2 + F_3)I_R}{28.9I_o} \tag{12.45}$$

for the third pass; I_s is the ionization rate from surrounding sources, I_R is the ionization rate from the roof at the start of decontamination, and F_1, F_2, and F_3 are the fractions of I_R remaining after each of the three consecutive passes. The over-all value of RN_2'' for n passes, all at the same rate, is

$$RN_2''(n) = \frac{I_s + (1/2n)\left[1 + 2(F_1 + \cdots F_{n-1}) + F_n\right]I_R}{28.9I_o} \tag{12.46}$$

The data of Table 12.9 for RN_2'' are plotted as a function of the fraction-remaining sums in Figure 12.3. Since each roof had different relative values of I_s and I_R, the two parameters could be evaluated only from the single pass data even for the experiments in which 2 or 3 passes over the roof were made. Since the observed I_o used to compute RN_2'' was undoubtedly not the open field value, the values of RN_s and RN_R in the figure are not equal to $I_s/28.9I_o$ or $I_R/29.8I_o$, respectively. However, within the limits of accuracy of the data, the linear representation appears to be satisfactory for use in estimating RN_2'' for firehosing roofs.

The roof firehosing setup times for the Complex II experiments were generally less than for Complex I. This was, in part, due to the use of a fire engine instead of a trailer mounted pump; also, in the Complex II experiments, more attention was given in preplanning and pretraining of the crews. The roof firehosing setup times given in Table 12.9 do not, apparently, include the times

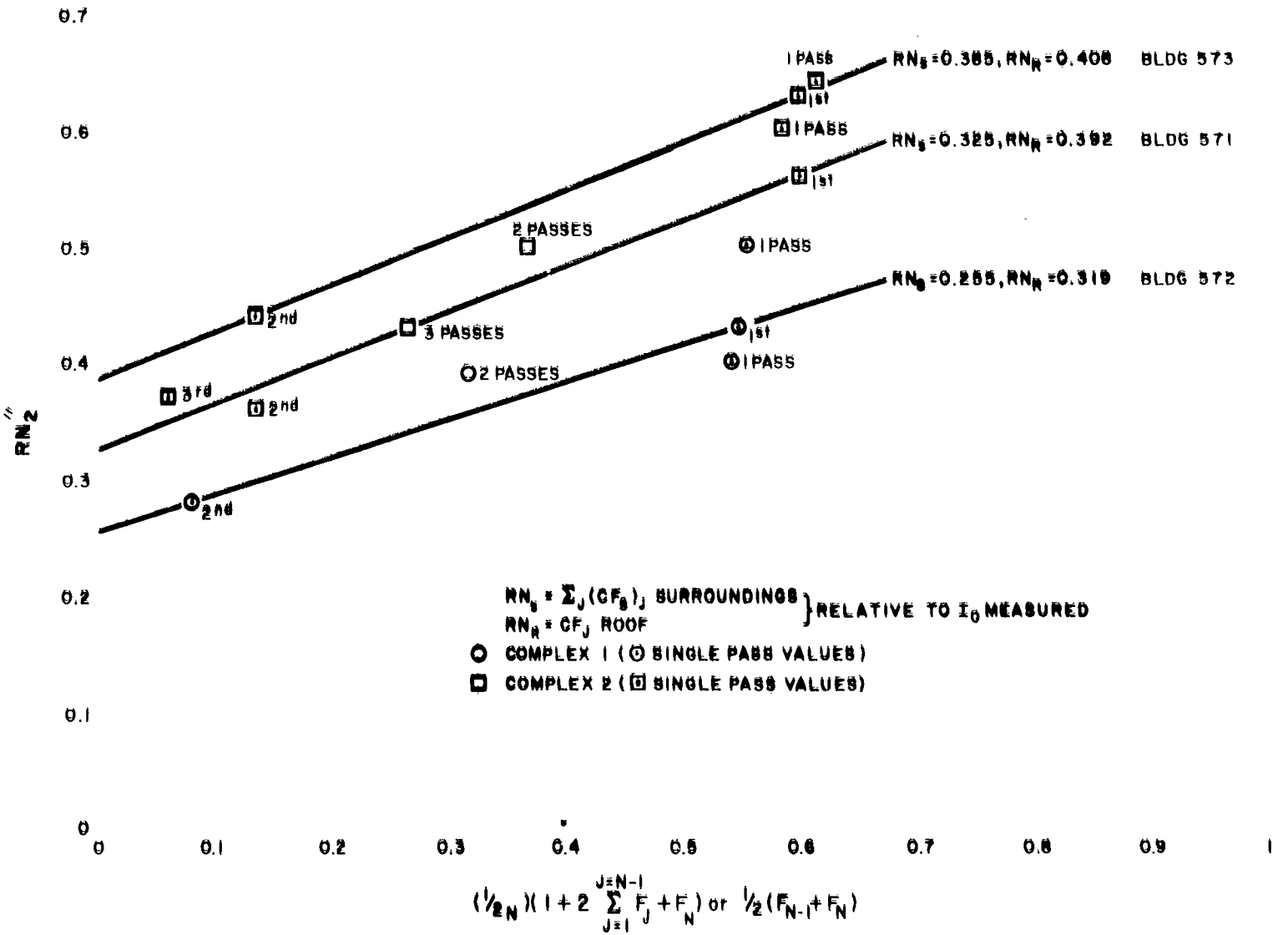
Table 12.9

SUMMARY OF TAR AND GRAVEL ROOF DECONTAMINATION DATA FROM CAMP PARKS COMPLEX I AND COMPLEX II EXPERIMENTS

Bldg. No. or Area	Area (sq ft)	Decontamination Time (min)	Rate (sq ft/nozzle-min)	Setup Time (min)	RN_2'' (flushing RN_2)	RN_2	F	Pass No.	No. of Nozzles
Complex I									
570	2700	26	104	31	0.50	0.76	0.11	1	1
571	2700	43	63	28	0.40	0.63	0.084	1	1
572	2700	23	59	26	0.43	----	(0.1)[a]	1	2
572	2700	9	150	--	0.28	----	0.065	2	2
572	2700	32	---	26	0.39	0.66	0.065	Both Passes	
573	5800	29	100	27	0.43	0.70	--	1	2
Complex II									
570	2700	36	75	17	0.60	0.70	0.17	1	1
571	2700	29	93	17	0.56	--	(0.2)	1	1
571	2700	28	96	--	0.36	--	(0.07)	2	1
571	2700	25	108	--	0.37	--	0.05	3	1
571	2700	82	---	17	0.43	0.52	0.05	Three Passes	
572	2700	35	77	20	0.64	0.75	0.23	1	1
573	5800	30	97	17	0.63	--	(0.2)	1	2
573	5800	28	104	--	0.44	--	0.07	2	2
573	5800	58	---	17	0.50	0.60	0.07	Both Passes	

a. Values in parentheses are estimated.

Figure 12.3
PLOT OF RN_2'' FOR FIRE HOSING OF TAR AND GRAVEL ROOFS AT CAMP PARKS AS A FUNCTION OF THE SUM OF THE FRACTION OF RADIATION REMAINING AFTER EACH DECONTAMINATION PASS ACROSS THE ROOF



for removing the crews and hoses from the roofs. In the illustrative computation here, an average time of 15 minutes for setup and 5 minutes for removing crews and hoses from each pair of houses is assumed. Since the street is cleaned, the same vehicle previously used in firehosing the streets can be used to pull the large 2-1/2 inch hose down the street.

If the roof firehosing setup procedure utilizes the cleaned driveways and streets, the contribution factor for the setting up time should be about the same as for the interior of the central house less 96 percent of the street and driveway source contribution to the intensity. On the basis of cleaning two houses at the same time, the estimated RN_2' for the setup time, from Table 12.5, is

$$RN_2' = \frac{12.6}{28.9} = 0.436 \quad , \; t = 20 \text{ min} \tag{12.47}$$

At the working rate of 100 sq ft/min for the two nozzles, cleaning the roofs of the two houses takes 25 minutes. The intensity contributions from the roofs and other areas at the center of the roofs of the first two houses that are decontaminated (i.e., the roof of the central house and one next to it), at the start and finish of cleaning, from Tables 12.2 and 12.5, are

$$I = 17.69I_c - 0.96x1.77I_c = 15.99I_c \quad , \; t = 0 \tag{12.48}$$

and

$$\begin{aligned} I &= 15.92I_c - 0.89x4.755I_c - 0.89x0.472I_c \\ &= 11.27I_c \qquad\qquad , \; t = 25 \text{ min} \end{aligned} \tag{12.49}$$

Since the intensity contributions from the sources on the more distant roofs are rather small, the decrease in their contribution to the leading nozzle team as each succeeding pair of house roofs along the street are cleaned, is neglected. Thus, during firehosing each pair of houses,

$$I = 15.92 - 0.189t)I_c \quad , \; t = 0 \text{ to } 25 \text{ min} \tag{12.50}$$

and for this general decrease in I during the decontamination of the two adjacent house roofs, the decontamination crew residual number is

$$RN_2' = 0.469 \tag{12.51}$$

The value of RN_2 for firehosing the roofs is the (20/45)x0.436 + (25/45)x0.469, or 0.454. The total time for firehosing all the roofs in the target complex unit is 14.6 hours.

Before estimating the RN_2 values for the earth or top soil removing techniques in decontaminating the back, side, and front yards, the disposition of the soil must be considered. The unpaved area per house in the hypothetical target complex unit is 5308 sq ft. Two inches of top soil has a volume of 32.8 cubic yards. If trucks, loaders, and a nearby disposal area are readily available, the material could be initially dumped in the nearest alleyway and/or street and then hauled away. However, such equipment may not be readily available. In this case, the question arises whether it is a practical procedure to dump the top soil in the backyards or alleyway.

If the dirt is piled in the alleyway along the width of the lot, 50 feet, the resulting pile would be about 6.4 feet wide and 5.5 feet high, assuming a cross-section shape of an equilateral triangle. A very rough estimate of radiation from this pile, assuming uniform mixing of the fallout particles with the soil, can be made from

$$I_s^o = 5.22\text{x}10^{-2} f_c \mu_A \overline{E}\ n_g \int_0^a e^{-\mu_\ell x} dx \quad \text{r/hr} \tag{12.52}$$

where I_s^o is the ionization rate at the surface of the soil, f_c is the fraction of the spherical volume about x = 0 containing the fallout; f_c is 1/2 at the center of the side of the pile and 1/6 at the top and bottom corner of the pile; the average value for use in Eq. 12.52 is therefore taken to be 1/3;

$\overline{E}$ is taken to be 0.5 Mev/photon as applicable for fission products from about 3 to 7 days after detonation,[7]

μ_A is the Klein-Nishina absorption coefficient for air and is $3.84\text{x}10^{-5}$ cm^{-1} for the 0.5 Mev photon,

n_q is the number of photons emitted per second per cm^3 of soil,

μ_ℓ is the Compton absorption or scattering coefficient for soil and is taken as 0.135 cm^{-1} for the 0.5 Mev photon (μ/ρ =0.090 cm^2/gm, ρ=1.50 gm/cm^3),

a is the half-distance along one side of the pile and is 3.2 feet or about 100 cm; for this distance the integral of Eq. 12.52 is $1/\mu_\ell$.

Using these parameter values, the average intensity at the surface of the pile of soil, from integration of Eq. 12.52, is

$$I_s^o = 2.47 \times 10^{-6} n_g \quad r/hr \tag{12.53}$$

For the surface density of one photon/sec per sq ft of ground surface, the mixing of the fallout particles with a 2 inch layer of soil would result in a photon emission density of 2.12×10^{-4} p/sec per cm^3. For this concentration, I_s^o is 5.23×10^{-10} r/hr.

From about 4 to 10 days after fission the ratio of r/hr per fission per sq ft to photons/sec per fission for unfractionated fission products is about 2.89×10^{-9} for the true air ionization at 3 feet above a smooth plane surface. This ratio would be about 2.20×10^{-9} for a calibrated instrument (see Chapter 2, Volume I). Combining the latter value with a terrain roughness attenuation factor of 0.75 to correspond to the reference open field ionization rate reduces the value of the ratio to 1.65×10^{-9} r/hr per photon/sec per sq ft. Thus, assuming 100 percent pickup of the fallout with the soil the ratio of the ionization rate at the surface of the pile to the initial open field ionization rate is given by

$$I_s^o / I(t) = 0.316 \tag{12.54}$$

The contribution of the sources in the fallout in the pile (as a line source) to the intensity at the back of the center house is

$$I_{64'} = 2I_s^o \int_o^{292} \frac{dx}{L^2 + x^2} = 0.042\ I_s^o \tag{12.55}$$

where the distance from the pile to the house, L, is 64 feet. At 30 feet from the pile, $I_{30'}$ is $0.092\ I_s^o$. Hence from Eq. 12.54,

$$I_{64'} = 0.0133\ I(t) = 0.38 I_o \tag{12.56}$$

and

$$I_{30'} = 0.0291\ I(t) = 0.84 I_o \tag{12.57}$$

According to the estimates given by Eqs. 12.56 and 12.57, the ionization rate due to the fallout sources in the pile at a distance of 64 feet away would be about 1 percent of the original open field ionization rate and at 30 feet away it would be about 3 percent of the original open field ionization rate.

Thus, where values of F between 0.05 and 0.10 for the backyards can be obtained by scraping or other top soil removal methods, the contribution from sources in the pile at the 30 feet distance is less than the contribution from the cleaned area. It is concluded therefore, on the basis of reduction in the ionization rate, that putting the contaminated top soil in the described pile is a satisfactory procedure. The pile could either be roped off indefinitely (i.e., for 1 to 2 years) or removed at a later time.

Accordingly, the plan to dispose of the top soil in a barrier along the alley (or against the back fence in case the alley is fenced off from the back yard) is accepted as part of the recovery operation.

The center of the back yard of the central house was used as the reference point for estimating the value of RN_2 for the bulldozer operator. Estimates of the contribution factors of various surface sources to the operator's exposure dose were first made without including the attenuation provided by the dozer itself. The receiver location was assumed to be at a height of 5 feet. The open field intensity is still $28.9I_o$ but the effective source radius for the 5 feet height is larger than 300 feet. The procedure used to make the estimates of the contribution factors is as follows:

1. From a line through the centers of the backyards (parallel to the alleyway), assign the contribution factor 28.9/2 to the sources across the line away from house(s) towards the alleyway.

2. Subtract from the 28.9/2 contribution factor half of the contribution factor for the center of the first backyard to be bulldozed.

3. Estimate, by use of the inverse square law, the contribution factors for the half of each backyard nearest the houses.

4. Subtract the estimates in Step 3 from 28.9/2 and assume that half of the remainder has an attenuation factor of 1/3 due to the houses and cleaned streets.

5. The initial contribution factor is the difference between 28.9 and the attenuated portion of 4 multiplied by the shielding factor of the dozer.

6. The contribution factors after bulldozing each yard are calculated by subtracting 0.95 times the contribution of the cleaned areas.

7. In bulldozing the yards across the alley from the cleaned yards, the contribution factor corresponding to that obtained from Step 1 and 2 above is 0.84 (see Eq. 12.57) plus the contributions of half of each backyard nearest the alley as given in Step 3 above.

The decontamination residual numbers and equipment attenuation factors for various equipments and methods reported by Sartor and Owen[9] are given in Table 12.10.

The calculations used in estimating the contribution factor for the bulldozer operator at the start of decontamination of the backyard of the central house are summarized in Table 12.11. The computational method probably gives a slight over-estimate of the contribution factor because shielding by fences, backyard structures, and trees is neglected. In yards with many small obstructions, hand cleaning with brooms, shovels and wheel barrows may be required, after bulldozing, to achieve the 95 percent average removal effectiveness; this additional work can either be lumped in with the shoveling decontamination effort around the houses themselves or be left as a final clean up measure after the major part of the operation is completed.

The sum of the contribution factors after bulldozing the first lot is, from Table 12.11, 0.38 times the sum of Steps 3, 4, 5 and 0.05 times Step 2, the indicated arithmetic gives a contribution factor of 5.88. The value of RN_2 for bulldozing the first yard is therefore

$$RN_2(1) = \frac{(10.12 + 5.88)}{2x28.9} = 0.277 \ , \quad t = 36 \text{ min} \tag{12.58}$$

The summary of the RN_2 estimates for bull dozing the remainder of the target complex unit back yards is given in Table 12.12. If 60 minutes is added to the working time to account for driving the bulldozer to location and for refueling, the mean value of RN_2 for the backyard bulldozing operation is 0.236.

The estimates of the contribution factors for the start of decontaminating of the side and front yards with shovels and wheel barrows at two different locations are shown in Table 12.13. The calculations were made by use of Eq. 12.12. The high value of the contribution factor for the side yard is due to the excess activity, assumed to be equal to $2I_o$, on the ground resulting from firehosing the roofs. The areas with the heavier contamination levels are cleaned first to reduce their source contribution to the intensity as soon as possible and to provide clean areas through which the wheel barrow men carry the soil to the back yards and put it on the pile made by the bulldozer.

Table 12.10

SUMMARY OF RN_2 AND A_s ATTENUATION FACTORS FOR EQUIPMENTS AND METHODS IN THE RECOVERY OF UNPAVED AREAS, AS DERIVED FROM DATA FROM COMPLEX I AND II EXPERIMENTS

Method or Equipment	Operation	RN_2	A_s
Plowing (D6 caterpillar)	Plowing open areas	0.23	0.38
Ford tractor (scraping)	Scraping lawns near buildings	0.42	0.66
Ford tractor (skip loading)	Loading spill in street	0.60	0.51
Motorgrader	Collecting spill in streets	0.53	--
Payloader	Loading spill in street	0.47	--
Dump truck	Loading in street	0.3	--
Shoveling (with tractor)	Scraping lawns near buildings	0.64	--
Shoveling	Scraping beds	1.27*	--
Shoveling	Scraping lawns	0.69*	--
Wayne Sweeper		--	0.60, 0.67**

* RN_2 high because of spill on the area from firehosing material off roofs and onto the areas which were scraped later.

** Lower number for open areas, larger number for streets with houses (low buildings) on each side.

If 5 men are used to firehose the streets, 6 to firehose the roofs, 1 man to operate the bulldozer, and 3 men allotted to supervision, scheduling and monitoring, then by using one man from each of the 39 houses, 24 men are available to form six 4-man shoveling and wheel barrow crews. If two such crews work on each of 3 adjacent lots separately and each crew cleans at a rate of 20 sq ft/min, the three lots would be decontaminated in 53 minutes. The total working time for the 39 lots is then 11.5 hours, or about 1.5 8-hour days.

The decontamination crew residual number for the shovel men is calculated for the two crews working the "outside" of the three lots. All crews start working at the back of the side yards. Assuming a linear reduction in the source intensity for the surface worked on and an F value of 0.1, the relative intensities (a) at the back of the side yard, (b) at the center of the front yard when the area is decontaminated to that location, and (c) at the center of the front yard when

Table 12.11

ESTIMATED RELATIVE CONTRIBUTION FACTORS FOR THE START OF THE BULLDOZING DECONTAMINATION OF BACK YARDS

Contributing Surfaces	Area (sq ft)	$h^2+r_c^2$	A_j	I_j/I	$\Sigma(I_j/I)$
1. Area beyond center line of back yards	--	--	1.0	14.45	
2. Area of back yard, center house	3200	--	1.0	11.74	
3. #1 less one-half of #2	--	--	---	8.58	
4. Adjacent back yards, house to center line (2)	1600	2,781	1.0	1.150	
2d removed backyards (2)	1600	10,281	1.0	0.311	
3d removed backyards (2)	1600	22,781	1.0	0.140	
4th removed backyards (2)	1600	40,281	1.0	0.079	
5th removed backyards (2)	1600	62,781	1.0	0.051	
6th removed backyards (2)	1600	90,281	1.0	0.035	1.766
5. Areas beyond line at the rear of the houses (towards the street) (14.45-#3-#4)x2/3				4.54	

$\Sigma_j I_j/I$(initial) = (28.9-1/3 of #5)xA_s(dozer) = 26.63x0.38 = 10.12

the first 3 lots are decontaminated were derived from the summary in Table 12.13. The respective intensity values, at the indicating working times, are:

$$I = 28.03\, I_o \quad , t = 0 \tag{12.59}$$

$$I = 8.61\, I_o \quad , t = 39 \text{ min} \tag{12.60}$$

and

$$I = 3.62\, I_o \quad , t = 53 \text{ min} \tag{12.61}$$

For a linear variation of I with t between the two time intervals, RN_2 for the outside crew is 0.522. This value is obtained by taking account of the areas decontaminated to 0.1 in Table 12.13 and the fraction of the time spent in each of the two time intervals of working as indicated by Eqs. 12.60 and 12.61.

Table 12.12

SUMMARY OF THE CALCULATION OF RN_2 FOR BULLDOZING BACK YARDS OF THE RESIDENTIAL TYPE TARGET COMPLEX UNIT

Back Yards Cleaned	Area	$h^2+r_c^2$	$A_s(1-F)$	I_j/I	$\Sigma_j I_j/I$(initial)	$\Sigma_j I_j/I$(final)	RN_2
None (at start)	3200	--	0.36	--	10.12	5.88	0.277
Adjacent	3200	2,525	0.36	0.46	9.66	5.42	0.261
2nd removed	3200	10,025	0.36	0.11	9.55	5.31	0.257
3rd removed	3200	22,525	0.36	0.05	9.50	5.26	0.255
4th removed	3200	40,025	0.36	0.03	9.47	5.23	0.254
5th removed	3200	62,525	0.36	0.02	9.45	5.21	0.254
6th removed	3200	90,025	0.36	0.01	9.44	5.20	0.253
Back Yards Across Alley with 5.5 ft Pile in Alley Way							
None (at start)	3200	--	0.36	--	7.85	2.94	0.187
Adjacent	3200	2,525	0.36	0.46	7.39	2.48	0.171
2nd removed	3200	10,025	0.36	0.11	7.28	2.37	0.167
3rd removed	3200	22,525	0.36	0.05	7.23	2.32	0.165
4th removed	3200	40,025	0.36	0.03	7.20	2.29	0.164
5th removed	3200	62,525	0.36	0.02	7.18	2.27	0.164
6th removed	3200	90,025	0.36	0.01	7.17	2.26	0.163

Bulldozing 13 yards, $RN_2 = 0.257$

Bulldozing 26 yards, $RN_2 = 0.212$

Bulldozing 39 yards, $RN_2 = 0.227$

Table 12.13

ESTIMATED CONTRIBUTION FACTORS AT TWO LOCATIONS FOR THE START OF DECONTAMINATION OF SIDE AND FRONT YARDS WITH SHOVELS AND WHEEL BARROWS

Contributing Area	Area (sq ft)	$h^2 + r_c^2$ (sq ft)	A_j	I_j/I
Location: Center Rear of Side Yards				
Backyards	-	-	1.0	0.72
Side Yard to 40' ($2I_o$)	1000	-	1.0	24.94
Side Yard 40' to sidewalk	900	-	1.0	0.31
Adjacent Side Yards to 40' ($2I_o$, 2 areas)	1000	2909	0.6	0.82
Adjacent Side Yards 40' to sidewalks (2)	900	5873	0.6	0.18
Nearest Front Yard	208	4250	0.8	0.04
2nd Nearest Front Yard	208	5200	0.6	0.02
Remaining Areas	-	-	-	1.0
			Sum	28.03
Location: Center Front Lawn Between Houses				
Lawn (25' x26')	650	-	1.0	9.98
Lawns Front of Houses	208	281	1.0	0.74
Lawns Front of Houses	208	4431	1.0	0.05
Lawns Front of Houses	208	13581	1.0	0.02
Lawns Front of Houses	208	1231	1.0	0.17
Lawns Front of Houses	208	6981	1.0	0.03
Lawns Front of Houses	208	17331	1.0	0.01
Lawns Front of Houses (2)	650	2509	1.0	0.52
Lawns Front of Houses (2)	650	10009	1.0	0.13
Lawns Front of Houses (2)	650	22509	1.0	0.06
Nearest Side Yard ($2I_o$)	1250	-	1.0	3.08
Adjacent Side Yards ($2I_o$, 2 areas)	1250	3953	0.6	0.76
2d Removed Side Yards ($2I_o$, 2 areas)	1250	11453	0.4	0.17
Lawns Across the Street	-	-	1.0	0.70
Remainder (14.45-6.56)x.05	-	-	1.0	0.40
			Sum	16.82

The relative intensities for the last lot decontaminated, as calculated from the summary of Table 12.13, are

$$I = 27.07\ I_o\ , \qquad t = 0 \tag{12.62}$$

$$I = 7.21\ I_o\ , \qquad t = 0.39\ \text{min} \tag{12.63}$$

and

$$I = 2.05\ I_o\ , \qquad t = 53\ \text{min} \tag{12.64}$$

The value of RN_2 for the crews working on this lot is 0.478. The RN_2 value for the shovel and wheel barrow crews in decontaminating all the side and front yards is taken to be the average of the RN_2 values for decontaminating the first and last lot; the value of RN_2 for the shovel and wheel barrow crew men is then 0.500.

The RN_2 values, decontamination working times, and decontamination starting times for the described decontamination operation in the assumed residential target complex unit are summarized in Table 12.14. The decontamination starting times for the short exposures were determined by calculating $I_a(t)$ from

$$D_2^* = RN_2\ I_a(t)\ \Delta t_{dec} \tag{12.65}$$

then determining the time after detonation and from the decay curve of Figure 11.2 for an $I_a(1)$ value of 2660 r/hr at 1 hour. This procedure is more accurate for short exposure times than the procedure in which the DRM curve of Figure 11.1 is used. The decontamination starting times, based on a D* 30r in 8 hours, for the longer decontamination working times were taken from Figure 11.3. The acceptable decontamination starting times for all methods vary from 3.1 to 5.5 days after detonation.

A suitable decontamination operations plan for the residential target complex unit, for the fallout level assumed in the illustrative calculations is as follows: (1) at D+5.5 come out of shelter and firehose the streets; (2) after firehosing the streets, change crews and begin firehosing the roofs; (3) start bulldozing the backyards immediately after the first two roofs are firehosed (this is about 4.6 hours after the decontaminating starting time at about D + 5.7);

Table 12.14

SUMMARY OF RN VALUES, DECONTAMINATION TIMES, DECONTAMINATION EFFECTIVENESS, AND DECONTAMINATION STARTING TIMES FOR 30r IN 8 HOURS (OR DURING DECONTAMINATION) FOR RECOVERY OF THE RESIDENTIAL TYPE TARGET COMPLEX UNIT

Method	RN_2	Δt_{dec} (hr)	F_{dec}	ΔDRM^a	t_{dec} (D + days)
Street Sweeping	1.04	2.9	0.08	0.0109	4.8
Firehosing Pavements	1.0	3.6	0.04	0.0113	5.5
Firehosing Roofs	0.45	14.6	0.11	0.0251	5.1
Bulldozing Backyards	0.24	24	0.05	0.0470	3.1
Shovel and Wheel Barrow	0.50	11.5	0.10	0.0226	5.5

a. $\Delta DRM = \frac{D_{\frac{1}{2}}^*}{RN_2 I_s(1)} = \frac{0.0113}{RN_2}$ for Δt of 8 hrs or Δt_{dec}, whichever is smaller

(4) start the shovel and wheel barrow crews when the bulldozer is scraping the 19th backyard.

If the bulldozer operator worked only 8 hours each day, the recovery operation would be finished at D + 8.7 providing the shovel crews started working when the bulldozing operation was about half completed. Actually, starting at D + 5.7, the bulldozer operator could work 14 hours before receiving an exposure dose of 30r. If the operator worked 14 hours the first day, and 10 hours the following day, the recovery could be completed in two days, giving an entry time into the houses of 7.7 days.

The effectiveness of the decontamination and the over-all residual number including the shielding due to the houses, for the procedure that uses fire-hosing rather than the street sweeping on the streets, is summarized in Table 12.15. With an RN_3^o value of 0.041 for the interior of the central house and a D* of 30r in 1 day, the entry time is 34 hours, or 1.4 days, after detonation for the people not on the decontamination crews. Since this entry time is less than that obtained from the planning dose for the decontamination crews, it is the planning dose for the crews, in this case, rather than the effectiveness of the decontamination methods, that actually controls the entry time.

Table 12.15

SUMMARY OF THE RN_3 AND RN_3^o VALUES FOR THE CENTRAL HOUSE AND CENTER OF THE STREET AFTER DECONTAMINATION OF THE TARGET COMPLEX UNIT

Surface Type of Contributing Sources	$k(cf)_j F_j$	
	Central House	Street Center
Roofs	0.028	0.004
Paved Areas	0.006	0.032
Lawns	0.024	0.010
Yards	0.024[a]	0.009
RN_3	0.082	0.055
RN_3^o	0.041	0.048

a. $\sqrt{(0.27x0.05 + 0.10x0.10)}$

An earlier entry time than 5.5 days could be obtained by allowing the decontamination crews larger doses, this alternative might be considered in the recovery schedule for high priority target units. Other ways of obtaining earlier entry times include obtaining additional bulldozers or other earth moving equipment, using street flushers to decontaminate the streets, or some combination of these alterations in the plan along with use of additional or spare crews and equipment operators.

The entry time into the central house without decontamination, based on 30r in 1 day, or 1000r in 1 year, for the assumed level of fallout, would be about 11 days. However, this entry time refers to staying in the house for some period of time, therefore, after a detonation. If it is assumed that two-thirds of the time is spent in the house(s)--or other buildings with an attenuation factor of 0.5--and one-third of the time is spent near buildings where the open field attenuation factor is 0.8, the average attenuation factor, $\bar{A}_J$, is 0.6. The entry time, with this attenuation factor at the location where I(1) is 2000 r/hr at 1 hour, is 17.5 days. The potential exposure dose from 17.5 days to infinity is about 1720r; the exposure dose, over the same time period, is about 1030r. Thus, without decontamination, an entry time of about 18 days is a more realistic entry time than 11 days.

In an open area containing no houses or other structures, the entry time for the 30r in 1 day, or 1000r in 1 year, planning dose is 52 days without decontamination. Thus attenuation factor values of only 0.5 to 0.6 reduce the entry time by a large amount when good shelters are available during the earlier emergency period.

The decontamination effort reduces the shelter stay time of all people in the target complex unit to less than 8 days at which time the central house area can be occupied. If adjacent areas are also cleaned by another group of workers, the whole target complex unit could be occupied at D+8 days.

Although, in the illustrative computation, the decontamination effort only reduces the shelter stay time by about 3 to 10 days, one obvious major benefit from the decontamination operation is the reduction in the subsequent exposure dose. For the exposure conditions after entry time where $\bar{A}_J$ is 0.6 with the described decontamination effort, the effective value of RN_3 is 0.043. The exposure dose from an entry time of 7.7 days to infinity is then about 100r. The total exposure dose to the decontamination crews, from the time at which they started working would be between 130r and 150r.

In the unit-average method of target analysis, all computations of entry times would be based on the RN_3 value of 0.1. The method involves no procedure for computing values of RN_2 for a given schedule of work. However,

assumed values of RN_2 can be applied to compute the entry times and decontamination starting times by use of the dose-rate multiplier curve in the same manner it is used in the point-location analysis.

The major items of equipment and supplies for the illustrative decontamination plan are listed in Table 12.16. The required water for the plan amounts to slightly more than 1600 gallons per residence lot, as determined from the nozzle calibration data of Figure 10.1. In case this quantity is not available from hydrants at the street corners because of damage to the water supply system and must be obtained from near by rivers, lakes, wells, or the ocean, this quantity would require 21 loadings for a 3000-gallon capacity tank truck.

Another alternate method of supplying the water from nearby water sources is by having additional hoses, pipes, and booster pumps available for rapid set-up. However, the times involved in setting up such alternate piping systems and the exposure dose to the setup crews would require a re-estimate of the entry times to see whether the alternative procedure is feasible and whether the gain in entry time and dose reduction over a partial decontamination (or some other plan) is sufficiently large for retaining the plan as a realistic alternative.

Additional equipment and supply items such as radiac instruments planning guides, extra work clothing, personnel decontamination facilities, and miscellaneous gear have not been listed in Table 12.16. Operational studies of radiological recovery processes have not as yet reported in sufficient detail all the required item types, and the amounts of each, that are needed to support the scheduled work.

The results of the Camp Parks experiments suggest that the target analysis procedure described above, when utilized, would eliminate the need for detailed monitoring of areas to be decontaminated the determination of I(1) from a decay curve and an intensity measurement at one or two selected locations will usually be sufficient to make a determination of the decontamination starting time and a detailed schedule of the whole decontamination operation. Ideally, planned schedules for a range of I(1) values and for a range of weapon yields and corresponding downwind distances would be prepared ahead of time to determine the feasibility of each of the plans and to establish requirements for needed equipment and supplies.

A significant research effort is still needed, however, to investigate the sensitivity of such plans in a general way on the properties of the fallout itself, on the fallout conditions that may arise from both single and multiple bursts detonated at different times, and on the characteristics of a variety of target complex unit types. The parameters that affect the end point solutions of decontamination problems given by the values of RN_2 and the entry times for these more complex conditions will generally be the same as those used in the illustrative calculation

Table 12.16

MAJOR ITEMS OF EQUIPMENT AND SUPPLIES NEEDED FOR THE DECONTAMINATION OF THE HYPOTHETICAL RESIDENTIAL TARGET COMPLEX UNIT

Equipment Item	Quantity Required
1 Firehosing Streets and Roofs	
500 gpm pump	1
2-1/2 in Hose	600 ft
1-1/2 in Hose	200 ft
5/8" fore nozzles	2 (streets)
3/8x5/16 elliptic, 30° fire nozzle	2 (roofs)
Gasoline	90 gal.
Men	11
Water	21,000 gal (streets)
Water	42,000 gal (roofs)
2 Bulldozing Backyards	
Bulldozer	1
Diesel Fuel	150 gal.
Men	1
3 Hand Cleaning Front and Side Yards	
Wheel Barrows	12
Shovels	12
Men	24
Gloves	24 pairs

Experimental tests such as those at Camp Parks described by Saylor and Owen[7] through which the target analysis procedures can be either verified or adjusted to empirical data, within an acceptable range of error, should permit application of the technique to a large variety of target complex units. Such tests would provide a basis for reasonable confidence that the predicted effectiveness of a realistically designed countermeasure system could be achieved.

12.7 Summary

The purpose of the detailed discussion and analysis of the residential area target complex unit in the previous sections was to illustrate methods for developing radiological recovery plans and procedures. The emphasis in the analysis on residential type areas does not mean decontamination of such areas should be given first priority in a recovery plan. Indeed, although the basic technical feasibility of decontaminating residential areas is not questioned, the fact that residential areas would be among the most difficult types to recover. In actual practice, most residential areas would require more effort, to achieve the same degree of effectiveness, than was estimated in the illustrative simulation.

A real radiological recovery plan must be developed whose first and basic objective is to sustain the survivors of a nuclear war. Thus, the first planning consideration is the recovery of priority facilities such as water works, food supply centers and sources, transportation facilities, power plants, fuel supplies, government facilities, hospitals, and any others of this type.

The second planning consideration must be given to the recovery of buildings and special areas to provide staging areas at which other nearby survivors could assemble to obtain food, water, medical care, and temporary lodging. The plan should allow for the contribution of these survivors in the recovery effort.

The choice of staging areas could be made on the basis of both shielding afforded by a large building or on the basis of the ease of decontamination of the selected area. Areas that could be decontaminated rapidly and effectively include: downtown paved areas, shopping centers with extensive paved parking space, schools with surrounding open areas, parks in which large motorized earth-moving equipment can be maneuvered, and open fields.

After a sufficiently large fraction or portions of the RADEP area (see Chapter 7) had been decontaminated to assure continued immediate survival of the people, and separated families had been together, the recovery of essential factories and places of business could be undertaken. At about this time some of the normal functions of government (other than those involving just recovery

could be resumed. Part of the surviving work force in the area could return to prewar work while others continued the clean-up operations of residential areas at a less urgent rate.

The experimental and theoretical data, and situation analyses, presented in this part (Volume II) of the report clearly establish the technical feasibility of applying radiological countermeasures. And furtner, the countermeasures can be designed to limit the exposure dose of people to a reasonable amount. The operational feasibility of these methods, however, remains essentially nonexistent and may remain so until many people become acquainted with more of the facts of life of this nuclear age.

CHAPTER 12 REFERENCES

1. Strope, W.E., and R.K. Laurino, Radiological Recovery of Fixed Military Installations, Navdocks TP-PL-13 (1953)

2. Lee, H., Estimating Cost and Effectiveness of Decontamination Land Targets, Vol. I. Estimating Procedure and Computational Techniques, USNRDL-TR-435 (1960)

3. OCDM, Fallout Shelter Surveys: Guide for Architects and Engineers, Np-10-2 (1960)

4. OCDM Engineering Manual: Design and Review of Structures for Protection from Fallout Gamma Radiation (1960)

5. Donovan, L.K., and A.B. Chilton, Dose Attenuation Factors for Concrete Slab Shields Covered With Fallout as a Function of Time after Fission, USNCEL-TR-137 (1961)

6. Strope, W.E., Evaluation of Countermeasure System Components and Operational Procedures, Operation Plumbbob, WT-1464 (1958)

7. The Effects of Nuclear Weapons, U.S. Government Printing Office, Washington 25, D.C. (1957)

8. Miller, C.F., and P. Loeb, Ionization Rate and Photon Pulse Decay of Fission Products from the Slow Neutron Fission of U-235, USNRDL-TR-247 (1958)

9. Sartor, J.D., and W.L. Owen, Radiological Recovery of Land Target Components. Complex I and II, USNRDL-TR (in preparation) (1961)

MAJOR SYMBOLS

Symbol	Definition
	--A--
A	Mass number of a nuclide
A_e	Effective gross attenuation factor for decontamination equipment operator
A_f	Defined by $FC_r(t)I(t)$; in fissions on foliage per sq ft of soil area
A_h	Effective attenuation factor for streetsweeper operator from radiation sources in the hopper
A_s	Attenuation factor for streetsweeper operator from surrounding radiation sources
A_α	Cloud radioactivity concentration in fissions per cubic foot
A'_α	Stem radioactivity concentration in fissions per sq ft
a	Nuclear explosion cloud radius at 6 to 8 minutes after detonation
a, a_j, or a_{rj}	Decontamination equation constant for absorption interaction (seawater and slurry type fallout)
a_L	Foliage contamination factor; fissions per gram of dry foliage divided by fissions per sq ft of soil area
a_z	Radius of stem or fireball at the altitude, z
$a_i(t)$	Radioactivity of the i^{th} nuclide at the time, t, after fission; in dis/sec per fission

Symbol	Definition
a_s	Stem or cloud radius at time of earliest fallout particle ejection
	--α--
α	Particle size parameter; defined as v_w/v_f
α_o	Size parameter for particles from cloud center; defined as X/h
	--B--
B	(1) Ratio of fission to total yield
	(2) Freundlich adsorption equation constant for elements in slurry type fallout
b	(1) Nuclear explosion cloud half-thickness at 6 to 8 minutes after detonation
	(2) Ratio of mass of solids to number of moles of radioactive element
	--C--
C(A)	Ratio of number of neutron captures to number of fissions (to form a nuclide of mass number A)
$C_e(t)$	Foliage croppage rate; in sq ft of foliage (dry) consumed per day
C_{fp}	Concentration of fission products in fallout; in moles of fission products per mg of fallout
C_ℓ	Radioelement concentrations in liquid phase of slurry type fallout; in moles per mg of liquid
C_o	Radioelement concentrations in seawater fallout drops
$(cf)_j$	Radiation contribution factor of area j

Symbol	Definition
C_s	Concentration of radioelements entrained in the mass of solids in slurry-type fallout, or, concentration of radioelements in the solid (soil) fallout particles; in moles per mg of solids
	--D--
D*	Planning dose or allowed dose; in roentgens
D or D_{ex}	Potential exposure dose; usually defined for a location at 3 feet above an extended plane source of radioactivity
D or D_x (1)	Instrument response factor
DRM	Dose-rate, or ionization rate, multiplier; defined as D/I_a (1)
d	(1) Particle diameter (2) Density of solids in seawater fallout
d_c	Crater depth (soils)
d_c'	Apparent crater depth (water)
d_m	Median diameter of fallout particles
d_w	Water depth (harbor detonation)
d_c^s	Crater depth in harbor bottom
d(t,1)	Decay-correction factor (to standard time after detonation, H+1)
	--Δ--
Δ DRM	Difference in DRM
ΔE_D	Dissociation energy
ΔE_T	Change in internal energy
ΔF°	Change in standard free energy of chemical reactants

Symbol	Definition
ΔH_v	Heat of vaporization
δ_λ	Ratio of crater depth for surface detonation(s) to crater depth for detonation(s) at other depths or heights of burst
	--E--
E	(1) Energy, of photons, etc.
	(2) Decontamination method effort, or energy expended; in man- or equipment-hours per unit area
ϵ_n	Efficiency coefficient for (some) decontamination methods; in fraction of fallout mass removed per cycle
	--F--
F, F_j or F_{rj}	Decontamination ratio, or fraction of fallout, or of a radioelement in fallout, remaining after decontamination
$FC_r(t)$	Foliage-contamination factor contour ratio; in fissions on foliage/sq ft of soil area per r/hr at time, t, after detonation
FD	Fraction of device per unit area
$FD_r(t)$	Fraction of device contour ratio; in $(r/hr)^{-1}$
F_m	Fraction of mass of fallout remaining after decontamination
F_r	Fraction of ionization remaining after decontamination
FP_g	Amount of ingested nuclides on particles passing through digestive tract (gut); in moles of fission products per day or dis/sec per day
$FP_r(t)$	Fission product contour ratio; in moles of fission products/sq ft per r/hr at time, t, after detonation

Symbol	Definition
$f_{s\ell}(\alpha)$	Total mass of solids and liquids per unit of yield for harbor-detonation fallout
$f(\alpha)$	Ideal (or unfractionated) inverse specific activity of land-type fallout; in mg/fission
$f'(\alpha)$	Ideal (or unfractionated) inverse specific activity of seawater fallout; in mg/fission
	--ϕ--
ϕ or ϕ'	Fallout model scaling parameter for computing standard intensities
	--G--
G°	Constant for referenced free energy change
	--γ--
γ	Surface tension of drop of liquid
	--H--
h	(1) Altitude of center of cloud at 6 to 8 minutes after detonation (2) Depth or height of burst
	--I--
I(1)	Standard intensity; observed ionization rate decay-corrected to H+1; in r/hr at 1 hr, at 3 feet above an open, uniformly contaminated, field
$I_a(t)$	Air ionization rate; in r/hr at time, t, after detonation
I_ℓ	The initially deposited amount of an element in the liquid phase of slurry fallout; in moles per sq ft
I_m	Initial mass level of fallout deposit; in gm/sq ft
I_o	Source intensity of a contaminated surface

Symbol	Definition
I, I_r, etc.	Ionization rate, radiation intensity, or other representation of the initial fallout deposit level
i	Number of moles of a given element in a drop of seawater fallout
	--K--
K or K_j	Decontamination equation parameter for seawater type fallout; in C-Level units
K^f_{cj}	Decontamination parameter for seawater fallout; in mg/sq ft
K_{rj}	Decontamination parameter for seawater fallout; in r/hr at 1 hr
K_a, K_c, K_s	Thermodynamic equilibria constants and/or solubility products
K_n	Various equation constants, for n = 1,2,3, etc.
$K(1), K_\alpha(t)$	Yield distribution contour ratio, same units as K(1)C(1); in r/hr per fission/sq ft or in r/hr per K/sq mi
K(E)	Efficiency coefficient, wet decontamination methods
K_{AB}	Equilibrium constant for formation of compound designated AB
K_I	Equilibrium constant for exchange reaction of an element
K_p	Equilibrium, or dissociation, constant in terms of partial pressures
K_λ	Mass-correction factor (surface detonation)
$k_{1,2}$	Fallout model scaling system parameter
k_j	Henry's law constant
k_ℓ	Mixing coefficient for the insoluble elements with the soil particles in slurry type fallout

Symbol	Definition
k_z	Cloud or fireball rate-of-rise equation constant
	--L--
$\bar{L}_j^\circ$	Relative partial molar heat content of element in gas phase
$\bar{L}_j$	Relative partial molar heat content of element in liquid phase
	--λ--
λ_N	Nuclear-scaled depth; defined by $h/W^{1/3}$ where h is in feet and W is in kilotons
	--M--
M	(1) Molecular weight (2) Mass of fallout particles remaining after decontamination; in gm/sq ft
$M_r^\lambda(t)$	Mass contour ratio; in mg/sq ft per r/hr at time, t, after detonation (for the fallout from a detonation at a nuclear scaled depth of λ_N)
M^*	Mass of particles remaining after decontamination after expending an excess of energy (i.e., infinite effort)
	--μ --
μ_A	Klein-Nishina absorption coefficient for air
μ_ℓ	Compton absorption or scattering coefficient
	--N--
N_A°	"Zero time" number of atoms/sq ft of radionuclide of mass number A
N_j	Mole fraction of element j in liquid phase
N_j°	Mole fraction of gaseous species of element j in vapor phase

Symbol	Definition
$N_j(A,t)$	Number of atoms of element j of mass chain A per 10^4 fissions
n_{fp}	Number of atoms or moles of fission products per unit area
n_j^o	Number of moles of element j in gas phase
n_j	Number of moles of element j condensed on or into liquid soil particle surfaces
$n(\ell,p)$	Number of moles of melted carrier in surface layer of particle
$n_o(p)$	Total number of moles of carrier in particle
$n(\ell)$	Moles of liquid carrier
n_α	Number of particles having size parameter α per unit volume of cloud
n_T	Total number of moles of gas molecules in fireball
	--P--
P	(1) Total pressure, in atmosphere (2) Kinetic power of a water stream
P_o	Initial pressure, in atmosphere
P_j	Ionization rate weighting factor for radionuclides of element j
PF_j	System protection factor
p	(1) Overpressure, in psi (2) Pressure, over the surface of a drop of liquid

Symbol	Definition
p_j	Partial pressure of element j over liquid phase
p_j^s	Sublimation pressure of element j
p_o	Vapor pressure of carrier material
	--Q--
Q	Water-flow rate through nozzle
Q_1	Energy in blast wave
Q_2	Energy in fireball
q_x	Terrain attenuation factor
	--R--
R	Molar Boltzman, or gas, constant
R_M	Remaining mass of fallout particles after decontamination, for infinite effort and a high initial level fallout deposit; in mg/sq ft
R_m	Remaining mass of fallout particles after decontamination, for infinite effort and a low or intermediate initial level fallout deposit; in mg/sq ft
RN	Residual number: ratio of exposure dose with a radiological countermeasure to the potential exposure dose (i.e., without a radiological countermeasure)
$R_r(\tau)$	Ionization rate remaining after decontamination, for a contact time of τ; in r/hr at 1 hr
$R_r(t)$	Ionization rate at time, t, after detonation (and after decontamination)
r	Fireball radius
$r_{fp}(1), r_x(1)$, or $r_\alpha(1)$	Gross fission-product ionization-rate fractionation number at H+1
$r_{jA}(\alpha)$	Fraction of a nuclide of element j and mass number A that is condensed on particles, or particle groups, designated by α

Symbol	Definition
r_m	Maximum fireball radius
$r_o(A)$	Fraction of an element of mass chain A condensed into liquid particles at the time that they solidify; a fractionation number
$r_o'(A)$	Fraction of an element of mass chain A condensed on the surface of solid particles; a fractionation number
$r_i(A)$ or $r_i'(A)$	Same as $r_o(A)$ and $r_o'(A)$, respectively, for a radionuclide designated by i
	--ρ -- (rho)
ρ	Density of liquid (or solids)
	--S--
S	Solid-to-liquid mass ratio
S_j	Solubility of an element or nuclide in 0.1 normal HCℓ
S_o	Solid-to-liquid ratio weighting factor
S(t)	Fraction of gross amount of radioactivity that is soluble in 0.1 normal HCℓ at time, t, after detonation
	--T--
T	Absolute temperature in degrees Kelvin
t_a	Fallout arrival time; time after detonation
t_c	Fallout cessation time; time after detonation
t_e	Time of entry into a contaminated area; time after detonation
t_{dec}	Decontamination starting time; time after detonation

Symbol	Definition
	--τ--
τ	Time, in days, of contact of fallout with a surface
	--V--
V	Fireball (or cloud) gas volume
V_0	(1) Original volume of heated air molecules (in fireball) (2) Initial liquid volume of a drop (seawater fallout)
V_2	Fireball volume at second temperature maximum
V_s	Volume of harbor-bottom crater
v_w	Wind velocity; a vector quantity for a particle group from its point of origin in the cloud to its location on the ground surface
v_f	Terminal fall-velocity vector of a particle or particle group
v_o	Particle fall-rate equation constant
	--W--
W	Total weapon explosive yield; in kilotons (of TNT)
w_L	Foliage surface density; in grams of dry foliage per sq ft of land area
w_o	Particle fall-rate equation constant

Symbol	Definition
	--X--
X	Downwind distance from ground zero
x	A distance or coordinate variable
x_h	Distance between sweeper operator and hopper
	--Y--
Y_A	Chain fission yield of mass number A; in atoms or moles per fission
Y_s	Half-width of stem fallout pattern to the 1 r/hr at 1 hr contour
y	Mass surface density of fallout particles (identical with I_m for land-type fallout); in mg per sq ft
$y_j'(t')$	Number of atoms per fission of element j (all mass numbers) at time, t', after fission
y_A	Fractional chain yield; in atoms per fission
	--Z--
z	Altitude coordinate; apparent altitude of fallout particle origins
z_c	Parameter defining cloud and particle rate-of-rise function; upper limit is h-b
z_s	Characteristic altitude at which first large particles fall away from rising fireball or cloud

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STANFORD
RESEARCH
INSTITUTE

MENLO PARK
CALIFORNIA

Regional Offices and Laboratories

Southern California Laboratories
820 Mission Street
South Pasadena, California

Washington Office
808 17th Street, N.W.
Washington 5, D.C.

New York Office
270 Park Avenue, Room 1770
New York 17, New York

Detroit Office
The Stevens Building
1025 East Maple Road
Birmingham, Michigan

European Office
Pelikanstrasse 37
Zurich 1, Switzerland

Representatives

Honolulu, Hawaii
Finance Factors Building
195 South King Street
Honolulu, Hawaii

London, Ontario, Canada
85 Wychwood Park
London 14, Ontario, Canada

London, England
15 Abbotsbury Close
London W. 14, England

Milan, Italy
Via Macedonio Melloni 40
Milano, Italy

Tokyo, Japan
911 Iino Building
22, 2-chome, Uchisaiwai-cho, Chiyoda-ku
Tokyo, Japan